令和３年度

地球温暖化対策における国際機関等連携事業

技術革新によるエネルギー需要変化に関する
モデル比較国際連携事業

成 果 報 告 書

令和４年３月

公益財団法人 地球環境産業技術研究機構

令和３年度地球温暖化対策における国際機関等連携事業委託
（技術革新によるエネルギー需要変化に関するモデル比較国際連携事業）

概要

地球温暖化は、地球全体の環境に深刻な影響を及ぼすものであり、気候変動枠組条約（UNFCCC）締約国会議(COP)の場等においてもその解決及び、対策の必要性が強く求められている。しかし、地球温暖化は、世界のあらゆる国、様々な部門に影響を与える一方で、地球温暖化が与える影響は均一ではなく、影響先も多様である。また、各国において取り得る緩和策、緩和費用にも差異が大きい。そのため、真に有効な対策を実現するためには、各国・各部門の様々な状況を考慮することが重要と考えられる。

2015年末のUNFCCC第21回締約国会議（COP21）で合意された「パリ協定」が、2016年11月に発効した。さらに、2020年からパリ協定が本格的に運用開始となり、今後は、パリ協定のルールにもとづく、プレッジ＆レビューの運用が本格化した。2021年11月には、COVID-19の影響により１年遅れとなった第26回締約国会議（COP26）が英国グラスゴーで開催され、パリ協定の詳細ルールの策定の内、協定６条に関する市場メカニズムに関連したルールの策定もようやく合意を得た。また、世界の平均気温の上昇を1.5℃に抑える努力を追求することを決意すると合意した。COP26に先立ち、多くの国と地域が、2050年までのカーボンニュートラルを表明し、温暖化への対応は、国際的にも成長の機会と捉える時代に突入した

こうした情勢の中、日本政府は、2020年10月に、菅前総理が「2050年までに、温室効果ガスの排出を全体としてゼロにする、すなわち2050年カーボンニュートラル、脱炭素社会の実現を目指す」ことを宣言し、2020年12月に経済産業省が中心になって、「グリーン成長戦略」を策定した。そして、2021年4月には、2030年の温室効果ガス排出削減目標を2013年度比26%減から46%減、更に50%減の高みを目指すと目標の深堀を行った。2021年10月には、第6次エネルギー基本計画が閣議決定され、また、地球温暖化対策計画、および、パリ協定に基づく成長戦略としての長期戦略についても改定し閣議決定された。

気候変動に関する政府間パネル(IPCC)では、2018年10月に1.5℃特別報告書が承認、公表された。この特別報告書では、国際応用システム分析研究所 (IIASA)を中心に開発されたAI等の技術進展や社会変化を伴いながら、低エネルギー需要を実現するLED (Low Energy Demand)シナリオが提示され、注目された。しかしながら、現時点においては、その定量的かつ包括的な分析は未だ十分にはなされていない。現在IPCCにおいては、第６次評価サイクルが本格化しており、気候変動に関する最新の科学的知見の提供が求められているところである。従って、環境と成長の好循環を実現すること、加えてIPCCの要請に対して我が国が積極的に貢献していくためにも、IPCCに対して、需要サイドの技術革新や社会変革がもたらすエネルギー需要の変化について、定量的かつ包括的に分析をインプットしていくことは極めて重要である。

本事業では、最新の科学的知見や国際交渉の動向も踏まえながら、①エネルギー需要サイドの技術革新と、②それに基づき生じる社会変化、③さらにそのCO_2排出削減への影響等について調査、分析、評価を行うとともに、④各国の主要研究機関と共に当該シナリオに対する比較研究を行った。

これらにより、国際的な研究コミュニティにおいて主要な気候変動シナリオの位置づけを主流化していくことに加え、IPCCの報告書へインプットしていくことを目的として実施した。なお、本事業は、国際的な通称として、EDITS（Energy Demand changes Induced by Technological and Social innovations）と命

名している。国際的にアピールしていくため、下記のようなロゴマークも定めることとした。

EDITS
Energy Demand changes Induced by
Technological and Social innovations

EDITS ロゴマーク（下段は、左から産業、建築、運輸、データ、定性的シナリオの作業部会）

エネルギー需要側の対策の分析は、部門毎にモデルを作成し、分析されることが従来では大半であった。また、統合評価モデル（IAM）による分析では、エネルギー需要側は対策をマクロ的に簡略に扱い、需要シナリオのように外生的な想定で分析が行われることが大半であった。しかし、デジタル化の影響などは、製品やサービスに体化されるエネルギーやCO_2 排出を含めて、セクター横断的に省エネルギー、CO2 排出低減が誘発され得るものであり、従来の分析では限界がある。本EDITS プロジェクトでは、国際的な連携の下、新たな技術動向、そして、社会的な変化を包括的に評価し、国際的なモデル比較分析も通しながら、新たな対策の道筋を示そうとするものである。現在の国際的な最新の知見の集約と具体的な作業の進展があった。

具体的には以下の項目について研究調査等を進めた。

（１）技術革新がもたらす CO_2 排出量削減やエネルギー需要の変化についてのコンピュータモデルを用いた総合的な分析・評価

国際応用システム分析研究所 (IIASA)を中心に開発された、AI等の技術進展や社会変化を伴いながら、低エネルギー需要を実現するLED (Low Energy Demand）シナリオに基づき、技術革新がもたらすCO_2排出量削減やエネルギー需要の変化について、定量的かつ包括的な調査、分析、評価を行った（下記の研究機関の報告書の①、⑳など）。

（２）各国の主要研究機関との比較研究

（１）で扱うＬＥＤシナリオに基づき、欧州や米国、アジア（中国・韓国・インド等）、中南米の主要国際機関、研究機関、大学等と共に需要サイドの変化に関連する複数の研究を行い、エネルギー需要サイドの変化について、比較分析、評価を行った。LEDシナリオの国際研究コミュニティにおける位置づけについては以下の通り主流化できた。

（詳細については各研究機関の報告書を参照）

① RITE においては、LED シナリオ関係の全体像を整理するとともに、運輸部門におけるライドシェアリング、カーシェアリングによる素材生産低減を含めた効果の分析、食品ロス低減効果の分

析、アパレルロス低減効果の調査と分析の方向性、3D プリンティングによるエネルギー需要低減に関する調査と分析の方向性についてまとめた。
②イタリア CMCC は、COVID パンデミックによりモビリティの制限がヨーロッパ 5 ヶ国の電力需要に与えた影響を整理するとともに、パンデミック後の世界でリモートワーク増加による業務部門エネルギー需要への影響を EDGE-WITCH モデルを使い、様々なシナリオについて分析した。
③中国清華大学は、中国の鉄鋼業界に焦点を当て、水素エネルギー活用を含む複数の技術シナリオにおけるエネルギー需要と CO_2 排出量の分析を実施した。
④韓国延世大学他は、韓国における人口と年齢・性別などの構造、世帯特性の変化、および行動変化を含む様々なチャンネルがエネルギー需要と温室効果ガス排出に与える影響を分析した。
⑤ブラジル COPPE は、統合評価モデル COFFEE-TEA の産業部門に関し、エネルギー技術と物質フローの詳細化を図るとともに、厳しいカーボンバジェットシナリオ下でセメントや鉄等の材料需要とグローバルサプライチェーンに及ぼす影響を試評価した。
⑥オーストリア BOKU は、主として産業部門における必要なエネルギー、物質、サービスに焦点を当て、低エネルギー、低物質の経路を探索しうる新しいモデルの構築を目的に、現在進行中のモデル文献レビューの状況と課題を記した。
⑦英国ティンダルセンターは、2000 年から 2018 年の期間に OECD 諸国と主要な発展途上国で化石 CO_2 排出削減を目的に導入されたエネルギーと気候政策の有効性をデータに基づき評価した。
⑧米国ウィスコンシン大学マディソン校の研究では、産業効率、エネルギー最終用途、エネルギープロシューマーをカバーする 3 つの事例研究を通して、低エネルギー需要(LED)の社会行動と技術を分析するためのイノベーションシステムのフレームワークの紹介を行った。
⑨米国スタンフォード大学は、北米の大幅な脱炭素化及び高度電化シナリオに関するエネルギーモデリングフォーラム（EMF）からの結論をまとめ、EDITS モデリングに関する洞察を提供した。
⑩タイ AIT は、インドの農村世帯が専用のソーラーマイクログリッドサービスシステムから得られるメリットを評価した。また、避けられない自動車の移動と発展途上国の視点に基づく e モビリティ、食品廃棄削減と食選択など持続可能な世界に向けての調査を行った。
⑪オランダのフローニンゲン大学は、どの戦略が人々の気候変動の信念、利他的および生物圏の価値観に基づいて行動する可能性を高めることができるか調査を行った。
⑫ハンガリーの中央ヨーロッパ大学は、建築部門における排出削減の可能性評価シナリオを提供するため、世界 11 地域における年次及び 1 時間ごとのエネルギー需要プロファイル及び建築物一体型太陽エネルギー生産プロファイルの推計と比較を行い、建築部門の年間 CO_2 排出量の算定を実施した。
⑬米国カリフォルニア大学は、デジタル化による全体のエネルギーバランスへの影響を理解するため、技術データセットとボトムアップモデル構築によるデータセンターのエネルギー需要の定量的評価を実施した。
⑭米国ローレンスバークレー国立研究所 (LBNL)は、技術的及び社会的イノベーションが、民生、産業、運輸、および分野横断におけるエネルギー消費及び CO_2 排出削減に与える影響を定量的に評価した。
⑮大阪大学は、2030 年から 2050 年までの日本の民生部門におけるエネルギー需要、及び CO_2 排出量の変化の推計を行った。
⑯東京大学は、運輸・建築分野の低エネルギー需要（LED）のシナリオ分析をすでに実施している既存のモデルから、エネルギーサービス、最終エネルギー、および CO_2 排出量の観点からモデル比較を提供。
⑰ITF-OECD は、輸送活動量の制御もしくは削減に向けたイノベーション及び政策、エネルギー需要、排出量の評価ツールの提供、運輸部門における非連続な需要変化の分析に向けたモデル更新、シェアモビリティの大規模導入による都市モビリティ及び排出削減への影響、世界の都市旅客輸送モデル及び移動需要、輸送の脱炭素化、および政策と技術開発の評価の可能性の提示を行った。
⑱オランダのユトレヒト大学は、メタリポジトリデータ WG はメタデータベース形式で作成を行った。 このデータベースは、低エネルギー需要の相互比較モデルで使用される予定である。
⑲ポルトガルのリスボン大学研究所は、デジタル・コンバージェンスと消費財のシェアが素材消費とエネルギー需要に与える相乗効果の研究をシナリオ分析を通じて行い、鉄鋼、アルミニウム、プラスチックなどの消費財に関連する 2030 年から 2050 年の需要モデルを提供した。 材料需要を削

減するための代替経路 また、先進国と発展途上国の両方のコンテキストで詳しく説明を行った。
⑳IIASA は、建築部門評価のためのモデリングツールの現状と、需要変革シナリオ構築の可能性をまとめた。また、12 月に開催したオンラインの WS について、研究動向など主要な内容を整理した。

これらにより、LED シナリオの国際研究コミュニティの構築を継続しており、来年度以降、更なる位置づけを主流化していく。

（３）IPCC 報告書へのインプット

（２）で行った調査、分析、評価について、学会や国際会議での発表や論文の執筆等を行った。加えて、IPCC第六次及び第七次評価サイクルにおいて報告書への掲載を目指すため、IPCCの執筆者を巻き込みながらLEDシナリオ等のインプット等必要な対応を実施した。ワークショップの参加者には、多くのIPCC 執筆者も含まれ（国際ワークショップ概要の付表の参加者リスト参照。WGIIIの副議長兼査読編集者1名、統括執筆責任者5名、代表執筆者15 名、SPM執筆者13名（ワークショップ参加者のみ。このほかにもワークショップ参加できなかった本事業参画者にもNan Zhou氏など、IPCC代表執筆者がいる。）、IPCC 報告書執筆への参考にもされた。

特に、IPCC第6次評価報告書では第5章にエネルギー需要の章が設けられ、本事業に参画している、Joyashree Roy氏 (AIT、タイ)とFelix Creutzig氏(MCCベルリン、ドイツ)が統括代表執筆者を務めた。また、Arnulf Grubler氏とEric Masanet氏は代表執筆者、Leila Niamir氏、Gregory Nemet氏、Julia Steinberger氏、Linda Steg氏、Charlie Wilson氏は執筆協力者である。 BBCのニュースで、Joyashree Roy氏は、この需要の章では、需要の社会科学の観点と、個々の消費者、コミュニティ、企業が責任ある消費、削減、設計、投資の選択を行う動機について考察していると述べた。責任ある生産と消費もこの章の範囲内であり、著者は行動変化の原動力は何かを検討するように求めている (https://www.bbc.com/news/science-environment-60798220)。

（４）国際ワークショップの開催

国際応用システム分析研究所 (IIASA)、（２）の共同研究実施の主要研究機関、その他、LEDと関連した専門家等による国際ワークショップを2021年12月9～10日に開催した。COVID-19の影響により、実開催は困難であったため、オンライン会議形式にて開催した。エネルギー需要部門の分析に関する情報交換、研究内容の共有を行った。詳細については次頁以降に示す。

Virtual Expert Dialogue on Energy Demand changes induced by Technological and Social innovations (EDITS)

2021年 12月 9～10日

会議報告

背景

EDITS事業の研究進展、情報共有を図るため、2021年12月9～10日にワークショップを開催した。ただし、COVID19の影響により、対面での開催は困難であったため、オンライン形式での開催とした。可

能な限り多くのタイムゾーンからの参加を尊重することができるようにコンパクトで的を絞った形で行われた。会議は、参加者の発言や対話を促すため、会議前後の電子メールでの意見交換、少数人数にグループ分け、ズームのチャットやMIROやGather.townなどのプラットフォームも活用するなど様々な工夫も取り入れた。 ワークショップ参加者は合計71名であったが、米国西海岸からの参加は時差のため、困難となった。

概要

EDITSは、強化された需要側の研究とモデリングに対する認知度の向上に基づいて構築されており、需要主導型のエネルギーシステムの変化をグローバルにかつ詳細レベルでより深く理解することを目指している。 EDITSコミュニティは、持続可能なエネルギーシステムへの移行、急速な気候緩和やSDGsの達成のための需要側解決策となるモデリングと分析、また伝達を強化するため、ギャップと可能性を特定する共同活動を追求している。

活動のレベルとエネルギーおよび資源需要の構造は、気候緩和行動の実現可能性、タイミングとコスト、またそれらのSDGの相乗効果とトレードオフの重要な決定要因としてますます認識されている。エネルギーと資源の需要自体は中間変数であり、提供されたエネルギーと他の資源を利用するのはサービスとアメニティである。1年間の集中的な作業と定期的な会議の後、コミュニティは2つの主要な目標を持ってワークショップに参加した。

-エネルギー需要/サービス需要の研究と政策立案の根底にある基本的なトピックについて話し合う。

-2021年の活動を評価するために、これまでの成果と進捗状況を確認し、来年以降の計画を立てる。

ワークショップは、次の 4 つのセッションで構成された。

- **セッション1:** EDITSのCOP26参加に関する報告と、低エネルギー需要の政策立案と輸送サービス提供に対する商業革新の実績例を含んだ動機付けスピーチを行った。
- **セッション2:** LEDの未来を尊重または表す環境構築ソリューションの実際の例についてより深い評価と議論につながるよう、ワーキンググループの2021年の活動と成果の概要報告の機会を設けた。
- **セッション3:** 低エネルギー需要のシナリオにおいての充足性と革新視点のバランスをとる方法について討論を行った。
- **セッション4:** コミュニティのすべてのメンバーに相談し、EDITSの範囲内での2022年以降の将来の方向性と具体的な計画についての見解を表明した。

セッション 1: モチベーションとフレーミング

2021年EDITSワークショップでは、秋元圭吾氏（RITE）がエネルギー需要の研究と政策支援がどのように注目を集めているかを振り返った。日本政府は、2030年までに46%の排出削減、2050年までにカーボンニュートラルに到達するという野心的な排出削減目標を設定した。新しいシナリオが必要であり、これらの目標を達成する方法を示す必要がある。この枠組みでは、政府は、継続的なサービスレベルを尊重しながら、大幅なエネルギー需要の削減に基づく戦略に特に関心を持っている。

これに対して、目標と野心が並んでおり、エネルギー効率を最初に促進するものとして尊重し、需要

を減らして供給やその他の技術への圧力を軽減することが不可欠であるため、EDITSが脚光を浴びている、EDITSは政策と産業の両方に接続する役割を担っている等コメントがあった。また、オーストリアの公共交通機関における取り組みの成功例と英国の独創的な低エネルギー需要モデリングが紹介された。

セッション 2: EDITS の科学的進歩と現実世界の革新から EDITS にもたらす教訓

2021年度のワーキンググループの進捗状況を簡単に確認した後、「都市のLEDシナリオの実際の革新から学習」に関する対話型セッションがSouran Chatterjee氏（中央ヨーロッパ大学、ハンガリー）によって設けられ、より広い建物セクター、つまり都市環境と建築環境における社会的、インフラストラクチャ、技術、および組織レベルでのニッチなソリューションと革新の範囲を探求した。

議論されたトピックは以下の通り。

- ✓ 科学界に産業知識をもたらすのに役立つ方法/活動は何か。
- ✓ LED シナリオは、実際の LED ケースの健康への悪影響をどのように捉えるべきか。
- ✓ 国、地域、さらには世界的な LED モデルの現在のニッチな例を拡張または展開する際の課題は何か。
- ✓ LED の例のリバウンド効果をモデル化する方法は。
- ✓ セクター結合：それは可能か。 いつまでに（市場とシステムの準備）?

セッション 3: エネルギー需要の変化に関する展望

元の低エネルギー需要シナリオ（Grübler et al. 2018）は、技術、社会、ビジネス、インフラストラクチャの各ドメインにおけるエネルギー需要の革新に焦点を当てており、上流に大きな影響を与える「効率戦略」に似ており、すべての人に適切な生活水準でサービスを改善することを保証している（Rao and Min 2017）また、低エネルギー需要は充足性によって達成されるべきであり、サービスまたは結果として生じるエネルギー条件のいずれかで消費における最大レベルを設けるべきであると主張している（Millward-Hopkins 2020; Steinberger＆Roberts 2010）。 居住空間のサイズの縮小化や生活水準の最低水準の達成など、LEDシナリオのナラティブを含む十分な側面がある一方、シナリオは、低エネルギー需要を達成するための主要なエントリポイントとして十分ではない。 EDITSネットワークの多くの議論では、充足性とエネルギー需要の革新的アプローチの違い、共通性、補完性がほのめかされてきたが、これらの側面は過去に明確に議論されていなかった。

セッションは Arnulf Grübler 氏（IIASA）が進行し、2 つのテーマによって開始した:

- ✓ 充足性とは何か、そしてそれが気候と幸福にどのように貢献するか
- ✓ エネルギー需要の革新とは何か、そしてそれが気候と幸福にどのように貢献するか。

セッション 4: 事前計画

このセッションは、コミュニティのメンバーが自分自身と広範囲の研究および政策コミュニティにとってEDITSの価値として何を見ているかを理解し、長短時間枠での計画をたてるために12-14人の小グループで議論が行われた。

ブレイクアウトグループでは、以下の質問と回答(提案)があった:

① あなた、あるいはあなたのチームは EDITS から何を得たか、今後は何を期待するか？

- 分野横断的な結合は価値があり、さらに強化する必要がある。(すでに様々な分野の代表者がいるが、社会学者や心理学者をさらに招待要、需要のナラティブがどのように政策ニーズにリンクし、政策に影響を与える可能性があるかを聞いてわくわくする等)
- ネットワーキングの価値 (EDITS は、エキサイティングな人々のネットワークとつながる多くの機会を与えた)
- EDITS は、需要側の視点のギャップを埋めるのに好ましいプロジェクトとして多くの人から引用された (影響を与えることは、私たちの成功の尺度になる)
- また、今後の活動におけるトピック追加が以下の通り提案された: 需要削減の全エネルギーシステムの影響、食品とデジタル化、行動と需要に対するデジタル化の影響を理解する、様々なセクターにおける LED 製品の 3D 影響等。

② EDITS における不均一性：メンバーシップと仕事における発展途上国の表現の改善に向けてどのように動くか？

- EDITS は、先進国と発展途上国のコラボレーションを強化する機会を提供する。
- モデルと研究は、データのギャップも反映して、発展途上国の発言の場を増やす必要がある。

③ 会議の周期や種類を変更する必要があるか？

a. 定期的な会議を評価する(パンデミックの間も連携を維持‐定期的な連携と会議は高く評価)
b. ほとんどの会議はオンラインで機能するが、少なくとも 1 回の対面会議があればありがたい。

④ 政策立案者は需要シナリオに関心を示しているが、EDITS ネットワークの研究と政策への影響のバランスにどのような関心があるか？

c. 少なくとも長期的には政策立案者とつながることが望ましい。(簡単に伝えられる意見記事を書く、EDITS 独自の頭脳力を最大限に活用し、需要側と幸福のために政策と資金調達の優先順位を再調整する必要性を説明する、政策の仲介者とチームを組む、自己言及を超える必要がある等)
d. 政策立案者への適切なメッセージを見つける(意思決定者にアピールするために、インフラ戦略と効率化戦略の利点（雇用など）を強調する、需要側と幸福のつながりに焦点を当てる)
e. 政策立案者を超えての連携(外部の業界関係者、政策立案者、消費者グループとつながることは歓迎される‐双方向の学習と対話の生成は、EDITS の学習を助け、影響を与えることもできる)

付表 1 国際ワークショップの参加者リスト

	国	組織	出席者	IPCC 関係者
1	Austria	International Institute for Applied Systems Analysis (IIASA)	Keywan Riahi	Ch.3 CLA *
2			Bas van Ruijven	
3			Arnulf Grubler	Ch.5 LA
4			Shonali Pachauri	Ch.2, LA *

5			Benigna Boza-Kiss	
6			Paul Kishimoto	
7			Volker Krey	Ch.4 LA *
8			Alessio Mastrucci	
9			Jihoon Min	
10			Caroline Zimm	
11			Pat Wagner	
12		University of Natural Resources & Life Sciences, Vienna (BOKU)	Dominik Wiedenhofer	
13			Jan Streeck	
14	France	International Transport Forum (ITF/OECD)	Luis Martinez	
15		Openex	Yamina Saheb	Ch.9 LA *
16	Portugal	DINÂMIA-CET of ISCTE-IUL	Nuno Bento	
17	Germany	Mercator Research Institute on Global Commons and Climate Change	Felix Creutzig	Ch.5 CLA *
18			Leila Niamir	Ch.5 CS *
19		University of Freiburg	Stefan Pauliuk	
20	UK	University of Leeds	John Barrett	AR5 Ch.5 LA
21			Marta Baltruszewicz	
22			Paul Brockway	
23		Imperial College London	Simon De Stercke	
24			Jarmo Kikstra	
25		University of Lausanne	Julia Steinberger	Ch.3 LA
26		Centre for Research into Energy Demand Solutions (CREDS)	Jonathan Norman	
27		University of East Anglia, Tyndall Centre for Climate Change Research	Charlie Wilson	Ch.5 Contributing Author
28	Netherlands	Utrecht University	Oreane Edelenbosch	
29		University of Groningen	Linda Steg	Ch.6 LA *
30	Italy	Polimi/CMCC	Giacomo Marangoni	
31		CMCC	Elena Verdolini	Ch.16 LA *
32			Massimo Tavoni	Ch. 3 LA
33	Hungary	Central European University	Diana Urge-Vorsatz	Vice Chair, Ch.8 RE *
34			Souran Chatterjee	
35	Belgium	University of Ghent	María Fernanda Godoy León	
36	Finland	WHIM	Sampo Hietanen	
37	Spain	Universidad Católica San Antonio de Murcia (UCAM)	Gabriel Carmona	
38	Switzerland	EPFL	Sascha Nick	
39	US	University of Wisconsin	Greg Nemet	Ch.2 LA *
40	Brazil	COPPE/UFRJ	Roberto Schaeffer	Ch.3 CLA *
41			Camila Ludovique	
42			Marianne Zotin	
43			Paula Borges da Silveira Bezerra	

44			Talita Cruz	
45			Leticia Magalar	
46	India	Prayas (Energy Group)	Srihari Dukkipati	
47			Narendra Pai	
48			Aniruddha Ketkar	
49			Atul Bhandari	
50		Center for Study of Science, Technology and Policy (CSTEP)	Poornima Kumar	
51	South Korea	Yonsei University	Tae Yong Jung	Ch.15 CLA *
52			Jongwoo Moon	
53		Korea Environment Institute	Yong-Gun Kim	Ch.2 LA
54	China	Tsinghua University	Xunmin Ou	Ch. 10 LA
55		Beijing Institute of Technology (BIT)	Biying Yu	
56	Thailand	AIT	Joyashree Roy	Ch.5 CLA *
57			Indrajit Pal	
58			Shreya Some	TSU *
59	Japan	University of Tokyo Japan	Yiyi Ju	
60			Masahiro Sugiyama	Ch. 12 LA
61		Osaka University	Yoshiyuki Shimoda	
62			Yohei Yamaguchi	
63		Research Institute of Innovative Technology for the Earth (RITE)	Keigo Akimoto	Ch.17 LA *
64			Miyuki Nagashima	
65			Ayami Hayashi	
66			Naoko Onishi	
67			Joni Jupesta	Ch.17 LA
68			Koya Yamada	
69			Atsuko Fushimi	
70			Yuko Nakano	
71			Takashi Honjo	

* AR6 SPM author

各研究機関報告書一覧

	Title	Research Institutes	Lead Authors
①	技術革新がもたらす CO2 排出量削減やエネルギー需要の変化の推計事例の調査と、コンピュータモデルを用いた総合的な分析・評価	地球環境産業技術研究機構	−
②	[1] Empirical analysis of the impact of the Covid pandemic on electricity demand [2] Modelling the implications of smart working from home on buildings' energy demand [3] Report Summary of the Synthesis working group (WG3) within the EDITS community work and participation to other WGs	CMCC/EIEE	[1] Giacomo Marangoni, Irene Malvestio, Massimo Tavoni [2] Giacomo Marangoni, Massimo Tavoni [3] Massimo Tavoni
③	Energy Consumption and CO2 Emissions in China's Iron and Steel Industry Industry: Potential Applications of Hydrogen Energy	Tsinghua University	Research group of OU Xunmin
④	Demographic Changes and Energy Consumption Behaviors in Korea	The Korean Society of Climate Change Research, Yonsei University	Tae Yong Jung
⑤	Impacts of materials demand growth in energy transition scenarios	The Universidade Federal do Rio de Janeiro, Fundação COPPETEC	Letícia Magalara, Marianne Zanon Zotina, Eduardo Müller-Casseresa, Roberto Schaeffer
⑥	Preliminary results from reviewing industry modelling of low energy and materials demand, net-zero GHG futures – towards a research roadmap for novel modelling for industrial sectors in response to deep demand-side transformations.	Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna (BOKU)	Dominik Wiedenhofer, Jan Streeck, Stefan Pauliuk
⑦	The effectiveness of energy and climate policy for reducing fossil CO2 emissions in energy demand sectors.	Tyndall Centre for Climate Change University of East Anglia (UEA), on behalf of UEA Consulting Ltd.	Theodoros Arvanitopoulos, Charlie Wilson
⑧	Social and Technological Innovation Pathways for Low Energy Demand	University of Wisconsin-Madison	Gregory Nemet, Leila Niamir, Elena Verdolini
⑨	Lessons Learned from EMF 37 with Implications and Suggestions For EDITS	Stanford University/EMF	John P. Weyant
⑩	Final Report	Asian Institute of Technology (AIT)	Joyashree Roy
⑪	Promoting reductions in fossil energy demand［要旨のみ公開］	University of Groningen	Linda Steg
⑫	Building self-sufficiency- A dream or reality? -Modelling the net-zero potential of the global building sector	Central European University on behalf of DBH InnoHub	Diana Ürge-Vorsatz, Souran Chatterjee, Gergely Molnar, Benedek Kiss

	Title	Research Institutes	Lead Authors
⑬	Technology datasets for modeling the energy demand of data centers	University of California, Santa Barbara	Eric Masanet, Thomas Wheeler
⑭	Assessment of the Roles for and Potential Impacts of Technological and Social Innovations on Energy and CO2 Emissions	Lawrence Berkeley National Laboratory International Energy Analysis Department	Nina Khanna, Hongyou Lu, Jingjing Zhang, Michelle Johnson-Wang, and Nan Zhou
⑮	2021 年度 日本の民生部門等におけるエネルギー需要変化の研究とりまとめ 報告書	大阪大学 大学院工学研究科 環境エネルギー工学専攻 下田研究室	下田吉之、山口 容平
⑯	Preparatory study for a model complementarlity exercise on demand-side innovations for climate change mitigation［要旨のみ公開］	東京大学未来ビジョン研究センター	杉山昌広
⑰	[1] Summary of updates on the modelling tools and outputs to be used by the EDITS network [2] Assessment of a demand disruptive phenomena: Shared mobility. How to incorporate simulation based results and data in aggregate models [3] Summary of activities within EDITS network [4] The 2020 global urban passenger transport model of the International Transport Forum	ITF-OECD	[1] Luis Martinez, Mallory Trouvé [2] Luis Martinez [3] Luis Martinez, Mallory Trouvé. [4] Mallory Trouvé, Luis Martinez
⑱	WP2 Data deliverable	Utrecht University	Oreane Edelenbosch, Paul Natsuo Kishimoto
⑲	Co-benefits of digital convergence and sharing of consumer goods to reduce carbon emissions and provide decent living standards	Iscte – University Institute of Lisbon	Nuno Bento
⑳	Annual Report Part 1: Energy Demand changes Induced by Technological and Social innovations (EDITS) Part 2: Progress report 2021-2022: the current state of building sector modeling	International Institute for Applied Systems Analysis (IIASA)	Part 1: IIASA Part 2: Leila Niamir

技術革新がもたらすCO_2排出量削減やエネルギー需要の変化の推計事例の調査と、コンピュータモデルを用いた総合的な分析・評価

地球環境産業技術研究機構（RITE）

第1章　はじめに

パリ協定では、産業革命以前比で 2℃未満に十分に低く抑え、また 1.5℃未満を追求するとされている。そして、日本政府も、2020 年 10 月に、1.5℃目標に相当するとされる「2050 年にカーボンニュートラルの実現を目指す」とした。また、COP26 では、世界各国は、世界の平均気温の上昇を 1.5℃に抑える努力を追求することを決意すると合意した。

1.1　エネルギー需要側対策の重要性とシナリオ動向

一方、気候変動に関する政府間パネル（IPCC）は、2018 年に 1.5℃特別報告書（SR15）[1]を公表した。そこでは、1.5℃を実現する、様々な排出経路が示されたが、とりわけ、Low Energy Demand (LED)というシナリオ[2]が注目をされた。これは、通常のモデル分析で示されるような、最終エネルギー需要よりもずっと小さなエネルギーを示すものである（図 1-1）。気候変動対策のみならず、持続可能な開発目標（SDGs）の同時達成にも寄与し得るとされる。文献 3)では、需要サイドの研究の強化の必要性が指摘されている。また、文献 4)では、需要サイドで多く見られる小規模技術の技術進展の速さ等についても指摘がなされている。分散型の小規模技術は、近年のエネルギー自由化市場、技術革新、デジタル化によりこれら新技術の活用が広がっていることを指摘している。

図 1-2 には、温暖化対策の全体像を示す。従来、社会構造変化・ライフスタイル変化は、外生的なシナリオとして分析されることがほとんどであった。しかし、その場合、どのような対策によって、低エネルギー需要が達成されるのか不透明であった。また、ライフスタイル変化は、教育といった文脈で議論されることが大部分で、しかし、教育の重要性は理解できるものの、全世界的に大きな効果として表れるためには時間軸が長いことと、効果が不透明な点が課題で、分析的な研究が十分なされてきていない。本研究では、デジタル化技術などの技術変化がきっかけとなり、社会構造変化・ライフスタイル変化に結び付く可能性を定量的に分析していこうという点で新規性が高い。図 1-3 にあるように、エネルギー需要側技術の進展により、ベースライン排出量自体が低位になるような変化がなければ、2050 年カーボンニュートラルや、大幅な排出削減の実現はとても難しいと考えられる。

一方で、低エネルギー需要社会の構築には、デジタルトランスフォーメーション（DX）がキーとなると考えられるが、一方で、DX によりデータセンターの電力消費量の増大等も予想される。このようなリバウンド効果も含めて、全体整合的な低エネルギー需要社会によってもたらされ得る、環境と経済の好循環、また、SDGs の同時達成による持続可能な発展の可能性を、信頼性の高い定量的なシナリオとして構築していく必要があり、多くの研究課題が残っている。

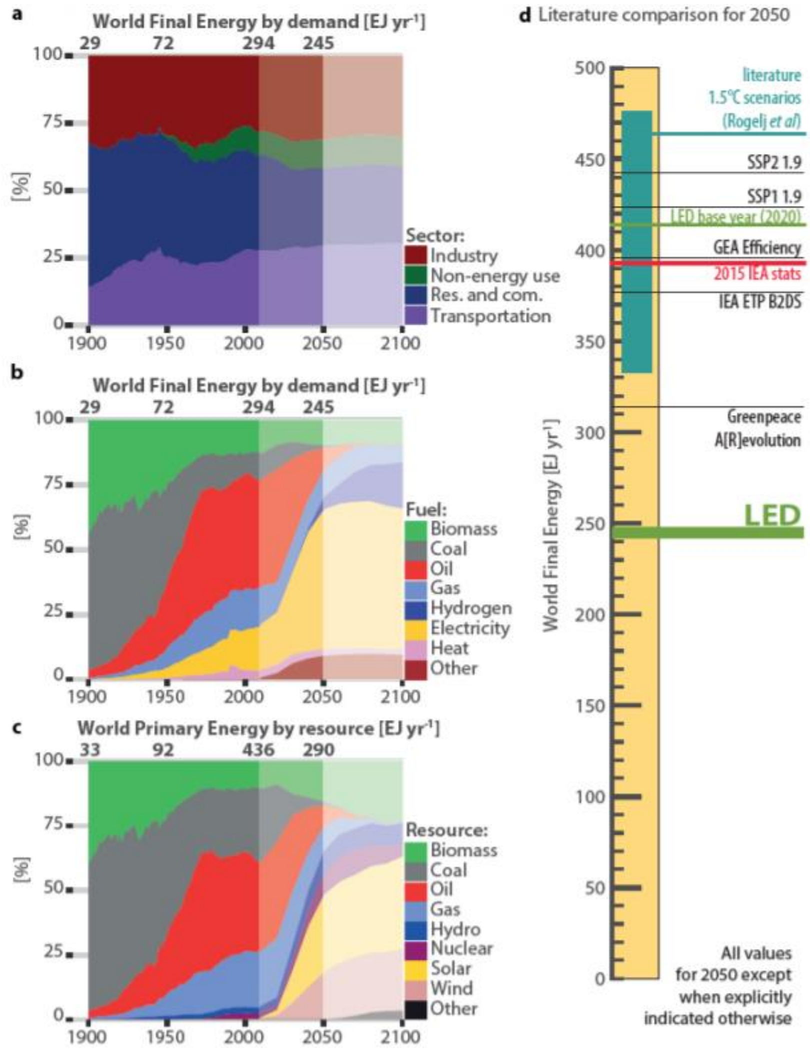


図 1-1 IIASA LED シナリオにおける最終エネルギー消費量 2)

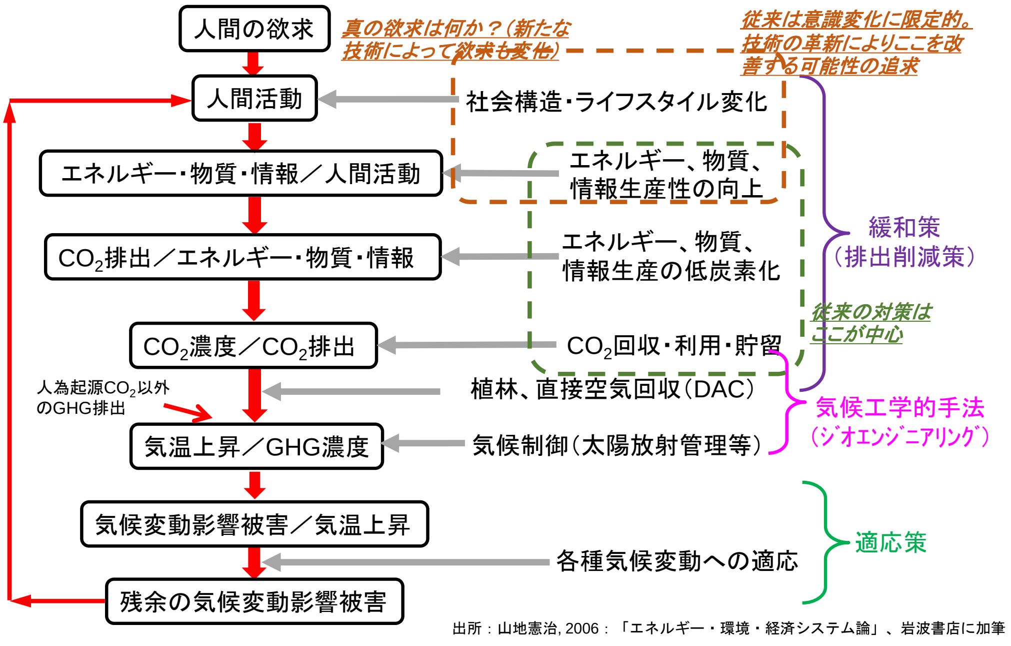


図 1-2 地球温暖化対策の基本構造と社会構造・ライフスタイル変化の位置づけ

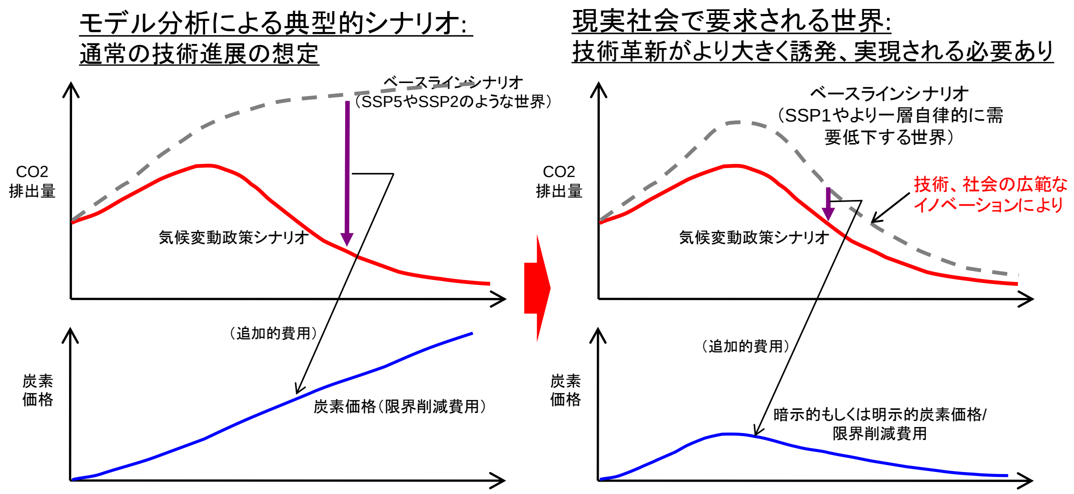


図 1-3 排出削減の経路と排出削減費用

1.2 本報告の構成

本報告では、エネルギー需要側対策の可能性として、第 2 章には、道路交通部門において完全自動運転車実現時のカーシェアリング、ライドシェアリングの進展とそれによるエネルギー需要、CO_2 排出削減低減の定量的な分析について記載した。第 3 章に食品ロスの低減によるエネルギー需要、CO_2 排出の低減の可能性と産業連関表を用いた定量的な分析について記載した。第 4 章ではアパレルロスの低減によるエネルギー需要、CO_2 排出の低減の可能性を記載した。第 5 章では 3D プリンティングによるエネルギー需要、CO_2 排出の低減の可能性について記載した。

第2章　完全自動運転車によるカーシェア・ライドシェア誘発による定量的な分析

本章では、デジタル化に伴うエネルギー需要、CO_2排出への影響を包括的に評価するため、完全自動運転車を取り上げ、それがカーシェア・ライドシェア普及に及ぼす影響と、更にその波及効果を含めた分析・評価を世界温暖化対策評価モデル DNE21+[1,2)]を用いて実施した結果をまとめる。本内容は、文献 3)として査読論文として採択された。分析の詳細については文献 3)を参照されたい。本章では分析したシナリオ結果を中心に紹介する。

2.1　モデル化の概要と想定

本分析では、完全自動運転車により、カーシェア・ライドシェア普及し、それが直接的な道路交通部門でのエネルギー需要低下につながるだけではなく、カーシェアに伴う自動車台数の減少による鉄鋼需要、プラスチック製品（エチレン・プロピレン）需要の低下に加え、立体駐車場の低減に伴う、コンクリート需要、鉄鋼需要の低減を推計し、総合的な分析を行った。完全自動運転車実現に伴う、ライドシェアリング、カーシェアリングに関係したパラメータ想定は図 2-1 のように想定した。

ライドシェアリング、カーシェアリングがどの程度進展し得るかは、モビリティ需要の密度に大きく依存すると考えられる。それに加え、既存の公共交通機関の整備状況などによっても影響され得る。しかし、DNE21+モデルは、国・地域については比較的細かい分割を行ってはいるものの、世界モデルであり、国や地域内におけるモビリティ需要の分布まで考慮して分析することは現実的ではない。また、公共交通機関の整備状況の違いを踏まえた分析を行うことも大きな困難が伴う。図 2-2 に記載のように、簡単に、カーシェアリングによる一台あたり年間走行距離の増加率が、人口密度によって説明できるとし、また、ライドシェアリングによる一台あたり乗車人数の増加率が、土地面積あたりの乗用車輸送サービス需要によって説明できると仮定し、図 2-2 のような想定を行った。この想定を基に、図 2-1 のとおりに計算を行い、各種モデル想定値を推計した（これによって推計されたパラメータの一部を表 2-1 に示す）。完全自動運転車有のシナリオにおいては、完全自動運転車は 2030 年以降に利用可能と想定した。

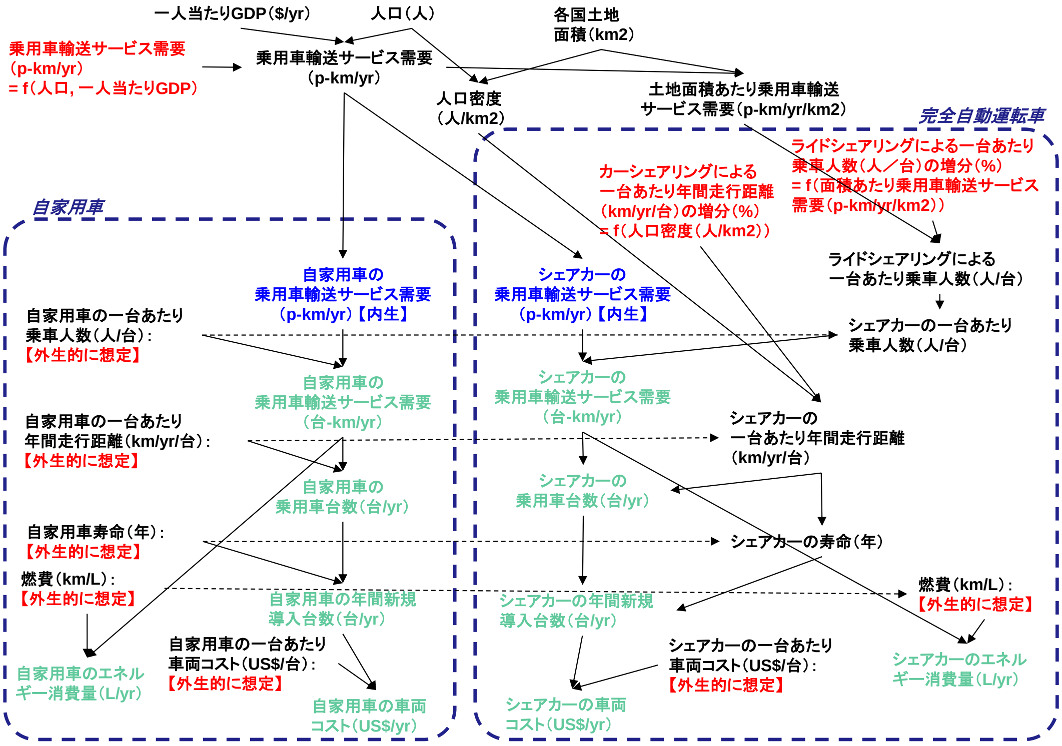


図 2-1 完全自動運転車と誘発されるシェアモビリティの想定

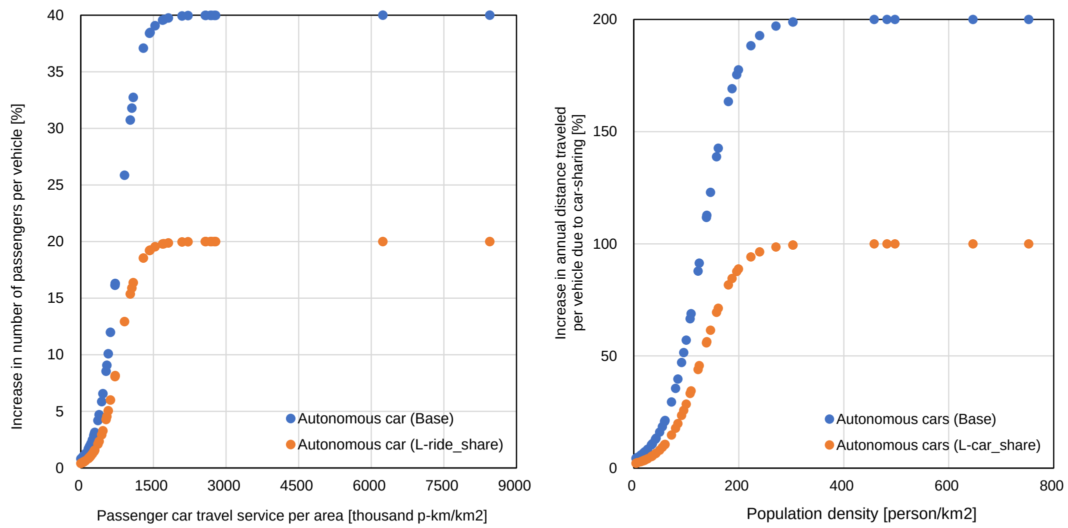


図 2-2 完全自動運転車によるライドシェア（左図）、カーシェア誘発（右図）の想定

注）図中プロットは、DNE21+における国・地域

表 2-1 完全自動運転シェアカーの想定

	非完全自動運転車 （自家用車）	完全自動運転車 （シェアカー）
車両価格	別途、車両タイプにより、それぞれ車両価格を想定	2030: +10000$ 2050: +5000$ 2100: +2800$ (非完全自動運転車比)
車の寿命	13–20 年	4–19 年
一台あたり 平均乗車人数	2050: 1.1–1.5 人 2100: 1.1–1.3 人	2050: 1.17–2.06 人 2100: 1.11–1.89 人

* 車寿命、一台あたり平均乗車人数の幅は、国・地域による差異の幅

2.2 分析シナリオの想定

社会経済シナリオについては、SSP2 と SSP1 ベースのシナリオの 2 種類を想定した。その上で、両シナリオについて、完全自動運転車によるカーシェア、ライドシェア誘発を想定しないシナリオと想定するシナリオの 2 種類、計 4 種類のシナリオを想定した（表 2-2）。一方、カーシェア、ライドシェアについては、とりわけ不確実性が高い。よって、表 2-3 のような感度解析シナリオを想定して分析した。また、これらの感度解析シナリオにおける具体的な数値想定は、図 2-2 の想定を基にすると表 2-4 のようになる。

表 2-2 社会経済シナリオとカーシェア・ライドシェアのシナリオ想定

	Socio-economic scenarios	
	SSP2	SSP1
No achievement of fully ACs	SSP2	SSP1
Car and ride-sharing associate with fully ACs	SSP2_AC	SSP1_AC

表 2-3 カーシェア・ライドシェアの感度解析の想定

	Scenarios
Base	Base scenario
L-ride_share	Lower increase in the number of passengers per vehicle due to ride-sharing explained by passenger car travel service per area
L-car_share	Lower increase in annual travel distance per vehicle due to car-sharing explained by population density
No material red	No consideration of reductions in steel, plastic, and cement productions

表 2-4 感度解析シナリオにおける完全自動運転シェアカーの具体的な想定（図 2-2 等から導出されるもの）

	Base (same in Table 6)	**L-ride_share**	**L-car_share**
Lifespan of shared car	4–19 years	Same as Base scenario	6–20 years
Number of passengers per vehicle	2050: 1.17–2.06 passengers 2100: 1.11–1.89 passengers	2050: 1.17–1.77 passengers 2100: 1.11–1.60 passengers	Same as Base scenario

排出削減シナリオについては、表 2-5 のように想定した。

表 2-5 排出削減シナリオの想定

	Emission reduction scenarios
REF	Baseline: without specific emission reduction policies
2DS	2 °C with >50% probability; -40% in 2050 compared with 2010
B2DS	2 °C with >66% probability; -70% in 2050 compared with 2010

2.3　モデル分析結果

(1) 乗用車保有台数

SSP2 および SSP1 について、排出削減シナリオをベースライン（REF)、2DS、B2DS のシナリオについて、ライドシェア、カーシェアを想定しないシナリオの世界の乗用車保有台数を図 2-3 に示す。

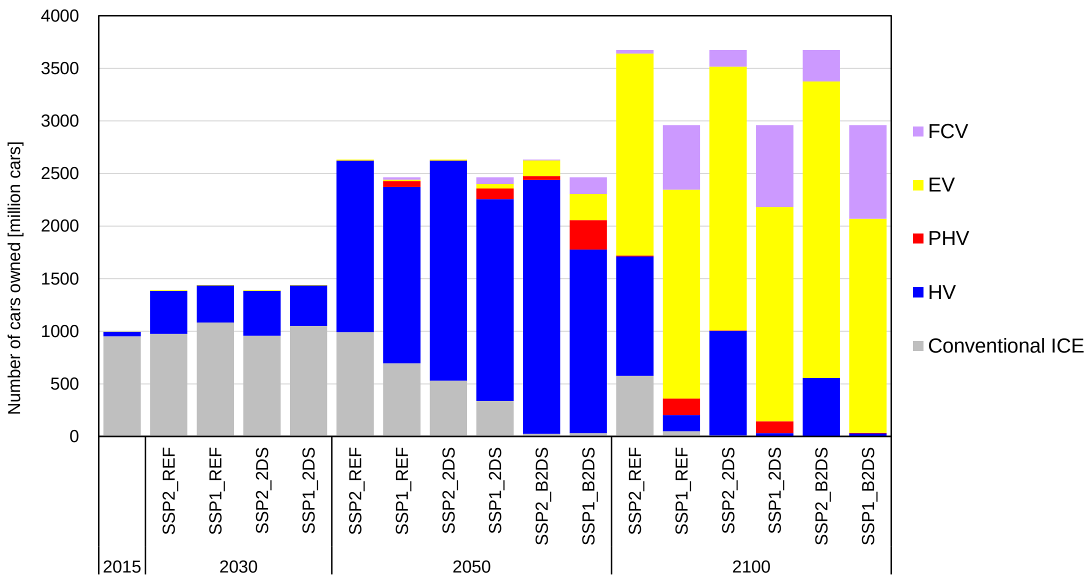


図 2-3 世界の乗用車保有台数（完全自動運転車想定無）

図 2-4 には、完全自動運転車によるライドシェア、カーシェア誘発を想定したシナリオの世界の乗用車保有台数を示す。保有台数は大きく低下する可能性が示されている。図 2-5 は主要国別に乗用車保有台数を示す。また、発電の CO_2 原単位についても表示している。人口密度や発電の CO_2 原単位にも影響され、完全自動運転車の経済合理的な比率や EV の経済合理的な比率が導出されている。図 2-6 は感度解析結果を示す。

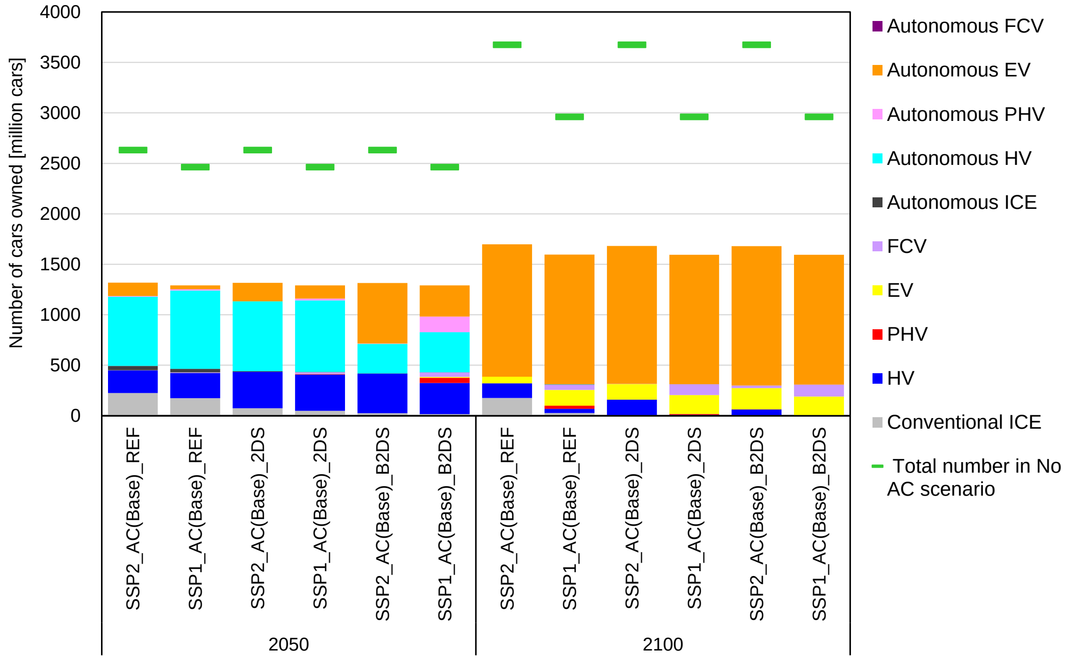


図 2-4 世界の乗用車保有台数（完全自動運転車想定有）

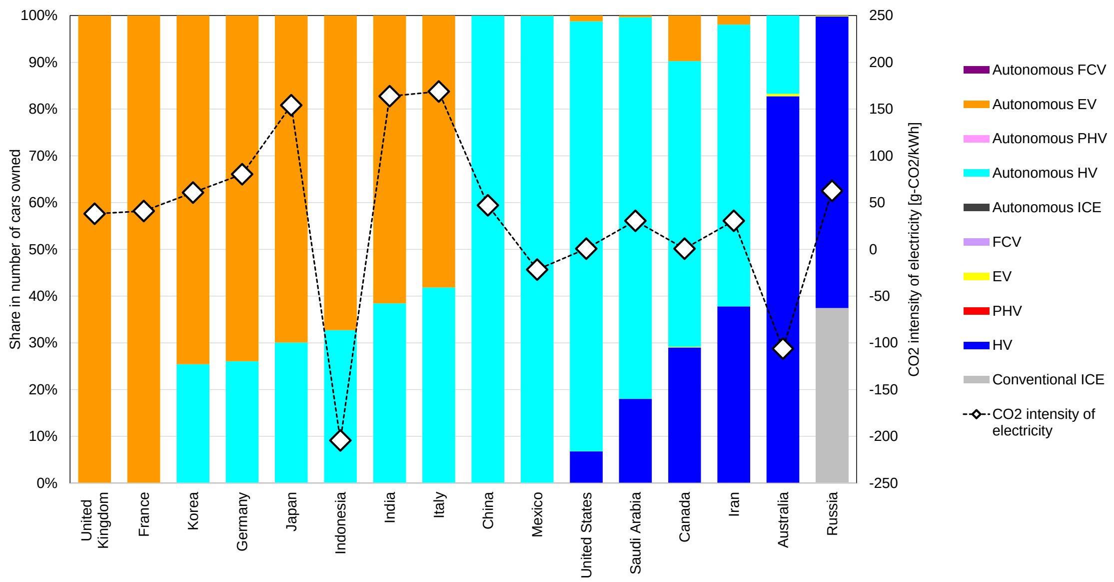


図 2-5 世界主要国別の乗用車保有台数（完全自動運転車想定有シナリオ、SSP2, 2DS, 2050 年）

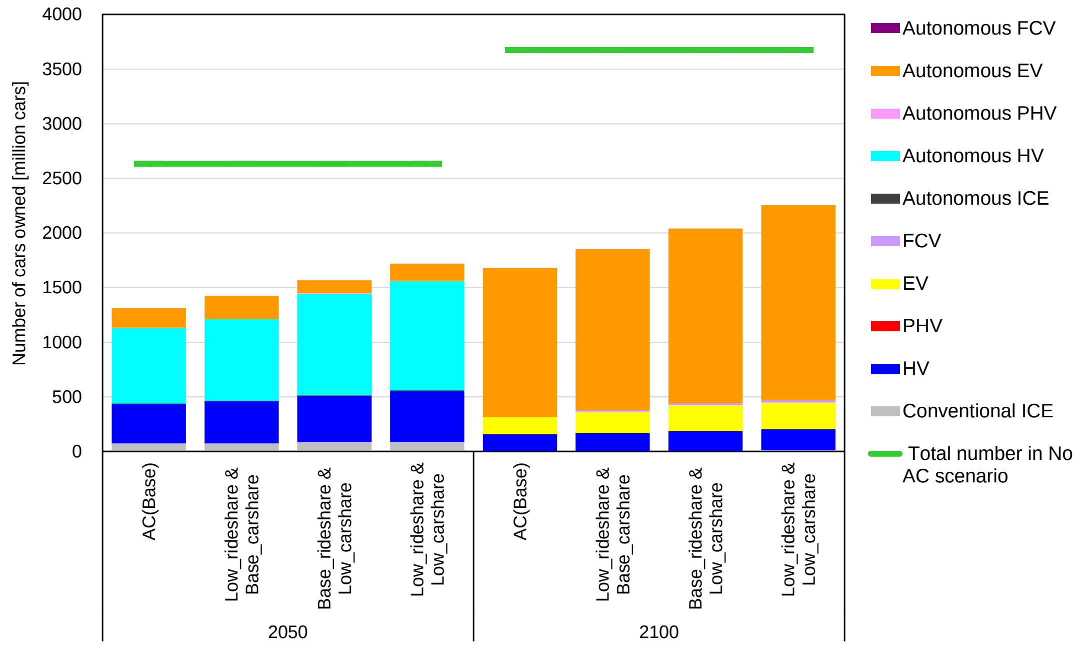


図 2-6 世界の乗用車保有台数（感度解析結果、SSP2, 2DS）

(2) 最終エネルギー消費量

図 2-7 には、世界の最終エネルギー消費量を示す。完全自動運転車を考慮したシナリオでは、最終エネルギー消費量の大きな低下が推計されるとともに、EV 化の進展もあわせて推計されている。

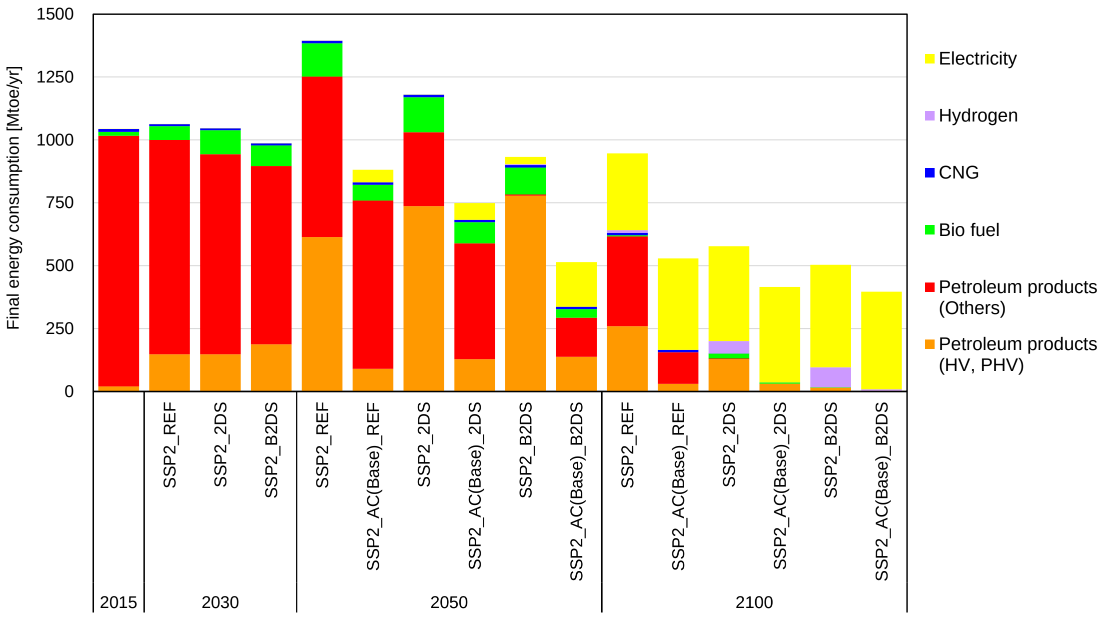


図 2-7 世界の最終エネルギー消費量

(3) 基礎素材生産量

表 2-6 には、2DS シナリオにおいて、完全自動運転シェアカーによる乗用車台数低下に伴う基礎素材の需要低下率を基準シナリオ比で示す。2050 年において、鉄鋼製品は▲3.7%、エチレン・プロピレンは▲1.1%、セメントは▲0.5%程度と推計された。必ずしも大きな低下ではないが、ライドシェアリングによる、自動車部門での直接的なエネルギー需要低下のみならず、エネルギー多消費の製品の需要低下による間接的なエネルギー需要低下も期待される。

表 2-6 完全自動運転シェアカーによる乗用車台数低下に伴う基礎素材の需要低下率（2DS：2℃，>50%シナリオ）

			Iron and steel	Ethylene and propylene	Cement
2050	SSP2	AC: Base	-3.7%	-1.1%	-0.5%
		AC: L-ride_share and L-car_share	-2.2%	-0.5%	-0.4%
	SSP1	AC: Base	-2.9%	-0.8%	-0.5%
		AC: L-ride_share and L-car_share	-1.8%	-0.4%	-0.3%
2100	SSP2	AC: Base	-4.5%	-1.3%	-0.8%
		AC: L-ride_share and L-car_share	-3.1%	-0.9%	-0.6%
	SSP1	AC: Base	-4.4%	-0.7%	-0.8%
		AC: L-ride_share and L-car_share	-3.1%	-0.6%	-0.5%

(4) CO_2 排出量

図 2-8 には、世界の 2050 年における部門別 CO_2 排出量を示す。完全自動運転車シナリオでは、非完全自動運転車シナリオと比べ、運輸部門での排出低減が見られる。また、表 2-6 で示したような素材の生産量低下も加わる。そのため、特に発電部門での BECCS 利用が低下し、2DS においては、発電部門の排出が非完全自動運転車シナリオでは正味マイナスであるが、完全自動運転車シナリオでは正味排出はほぼゼロに変わっている。

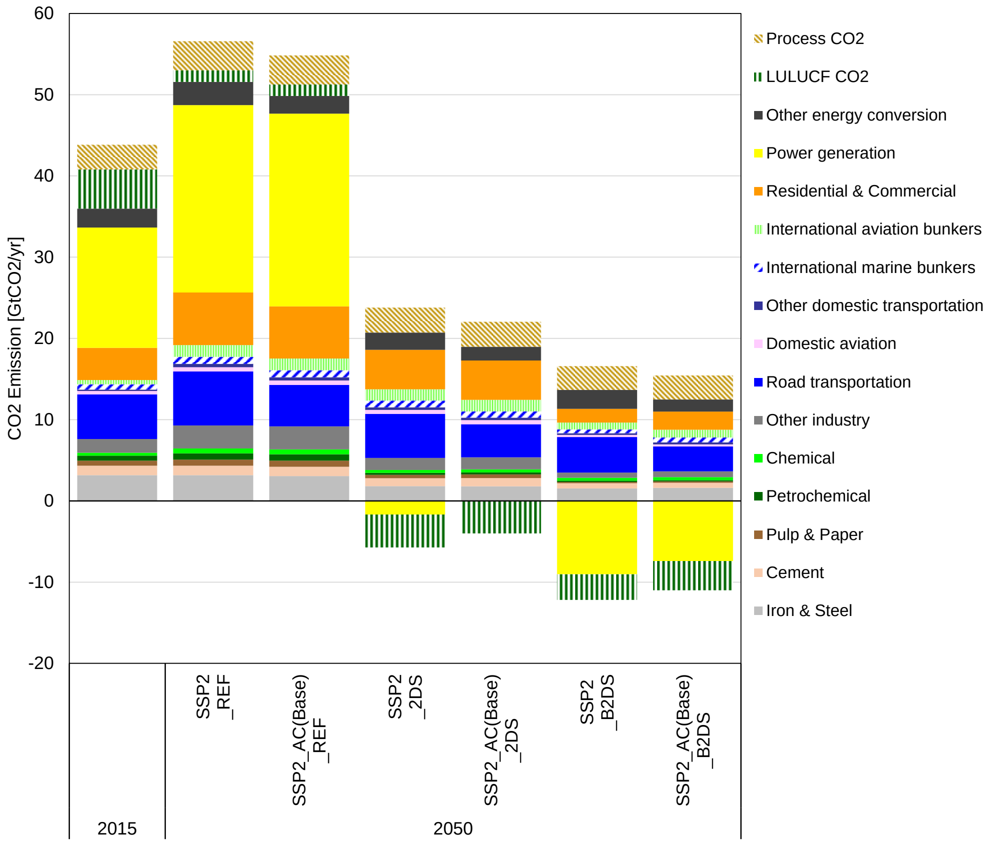


図 2-8 世界の CO_2 排出量

(5) CO_2 排出削減費用

表 2-7 には各シナリオにおける 2050 年の CO_2 限界削減費用と CO_2 削減費用を示す。大きなコスト低下が推計されたわけではないが、素材生産量低下の効果も若干ながら見受けられる。ここで考慮しなかった、より広範な素材生産量の低下を考慮した分析も今後検討すべき課題と言える。

表 2-7 2050 年の CO_2 限界削減費用と CO_2 削減費用

	Ride and car-sharing associated with fully ACs	No	Yes: Base		Yes: L-ride_share and L-car-share
	Material reductions (indirect impacts by the sharing)		No (direct impacts of road transport sector)	Yes	Yes
Marginal abatement cost ($/tCO2)					
2DS	SSP2	169	151	150	157

	SSP1	178	166	165	171
B2DS	SSP2	608	416	413	451
	SSP1	452	372	368	390
CO_2 emission reduction cost (trillion $/year); difference in total energy system costs from those in REF scenarios without AC under each SSP					
2DS	SSP2	1.70	-9.21	-9.25	-4.89
	SSP1	1.43	-7.42	-7.45	-3.60
B2DS	SSP2	5.79	-5.82	-5.87	-1.36
	SSP1	4.75	-4.44	-4.48	-0.43

参考文献（第２章に関するもの）

1) Akimoto K, Sano F, Homma T, Oda J, Nagashima M, Kii M (2010) Estimates of GHG emission reduction potential by country, sector, and cost, Energy Policy, 38-7, 3384–3393.

2) Akimoto K, Sano F, Tomoda T (2018) GHG emission pathways until 2300 for the 1.5 °C temperature rise target and the mitigation costs achieving the pathways, Mitigation and Adaptation Strategies for Global Change, 23(6).

3) Akimoto K, et al. (2021) Impacts of ride and car-sharing associated with fully autonomous cars on global energy consumptions and carbon dioxide emissions, Technological Forecasting and Social Change, 174, 121311.

第3章　IT 等の進展による食料システムにおけるエネルギー消費と GHG 排出の削減に関する分析

本章では、食料システムの中でも、近年世界的関心が高まっている食品ロス低減を取り上げ、世界各地域の食品ロスが IT 等の活用によって低減した場合の各部門の生産・サービス、及びエネルギー消費、GHG 排出量への影響を、産業連関表を用いて分析した内容について記す。

3.1　食料システムに着目する理由と本研究のねらい

食料は人間が生きていく上で必要不可欠であるが、我々の消費に至るまでは、農水産物の生産、加工、輸送、小売、調理、廃棄処理と複数のプロセスを経る。その一連を食料システムと捉えると、そこで消費されるエネルギーは世界の最終エネルギー消費量の約 30%[1)]、GHG 排出量は人為起源 GHG 総排出量（520±45 億 tCO_2eq/年）の約 21-37%を占める [2)]（図 3-1）。これらの値は、食料システムの境界想定（例えば、土地利用変化、原料製造、固定資本形成、輸出入品の扱い方）に依存し、様々な不確実性があるものの、食料システム全体で消費されるエネルギーや排出される GHG が相当に大きいことは推察できる。今後、主に発展途上国等で人口増加や経済発展に伴う食料需要の増大が予想される中、人々の食料需要を満たしつつ食料システム全体のエネルギー消費、GHG 排出の増大を抑制する事は、カーボンニュートラル社会を志向する上で重要である。

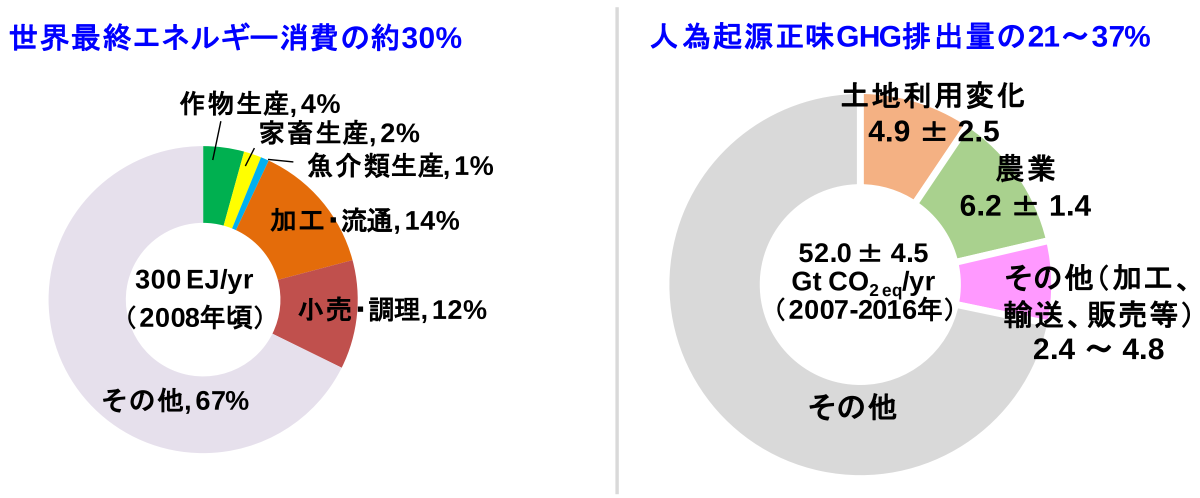


図 3-1 世界の食料システムのエネルギー消費量（左）と GHG 排出量（右）

一方、人の消費のために生産された食品の約 1/3、約 13 億 t が損失・廃棄されているとの報告もある [3)]。2015 年に採択された国連の持続可能な開発目標（SDGs）のターゲット 12.3 では、「2030 年までに小売・消費レベルにおける世界全体の一人当たりの食料の廃棄を半減させ、収穫後損失などの生産・サプライチェーンにおける食料の損失を

減少させる」という目標が掲げられた[4)]。これに関連し、日本、米国、EU、アフリカ連合[5),6)]等複数の国・地域で、2030年頃までの食品ロス低減目標が策定されている。各国・地域の食品ロス低減目標は、食品ロスとして考慮する範囲（可食部のみ/可食部と非可食部）、低減を目指す部門（収穫後の取り扱い/食品業と家庭/サプライチェーン全体）、さらに目標設定の基準（一人当たり量/地域全体量）等多様であるものの、食料システムは上述の通り多くの部門から成り立っていることより、食品ロス低減の影響は関連部門に波及し、エネルギー消費・GHG排出の削減に寄与すると考えられる。このような状況を鑑み、将来のエネルギーシステムに関するモデル分析でも、食品ロス低減を想定したシナリオが検討されつつある[7),8),9)]。但し、その食品ロス低減のための具体的な方策や各部門への影響は示されておらず、各部門の生産・サービス需要変化を考慮した包括的な分析を行うには情報が不十分である。

世界の各地域で食品ロスが発生する主な理由は、文献3)によると低所得国では、換金を急ぐあまり未成熟な作物を収穫し結局出荷せずに廃棄される、また収穫後の貯蔵・流通設備の不備による損失があげられる。一方、中・高所得国では販売機会喪失を避けるための過剰生産・廃棄や、消費段階での廃棄があげられる。後者に関し、米国等の小売や飲食サービスでは、Point Of Sales（POS）データを活用した需要予測による廃棄低減が検討されている[10)]。日本でもPOSと高度気象予測の情報、さらにSNS上の暑さ・寒さに関するつぶやき情報を活用した需要予測により、豆腐や冷やし中華つゆ等の食品廃棄が低減したという実験例がある[11)]。

そこで、本研究では、食料システムの中でも世界的に実現の可能性が高いと見込まれる食品ロス低減に着目し、世界各地域の食品ロスが低減した場合の、各部門の生産・サービス、及びエネルギー消費、GHG排出量への影響を定量的に分析することを目的とした。ここで、食品ロス低減の手段として、実証実験で低減効果が確認されている需要予測技術をはじめ、近年、普及、進展が著しい情報技術の活用を想定した。分析対象時点は世界の産業連関表として入手できた最新の2014年である。

3.2 主要な想定と分析方法

食品ロス[1]低減策は各地の食料システムによって異なりうる。本分析では、世界的に導入され、食品ロスの低減に寄与する可能性が考えられるものとして、表3-1に示す対策を取り上げた。このうち、POS情報を用いた需要予測は日本や米国、ナイジェリア、インド等の小売や飲食サービスで検討されているものである[10),12)]。買物・献立管理のアプリを活用した家庭の食品ロス低減策は、日本や米国を参考に想定した[10),13),14)]。倉庫整備は、特にアフリカやアジア等の途上地域で、農家の作物貯蔵やその他流通設備の不備によるロスが大きく[3)]、保存環境の改善が課題とされている[6),15)]ことを考慮したものである。これらの地域で課題とされる倉庫が整備された上で、食品業の需要予測や、家庭の買物・献立管理の対策も取りうると想定した。

[1] 本章では断りが無い限り「食品ロス」は可食部・非可食部の両方を含むものとする。

表 3-1 想定した食品ロス低減策と部門

食品ロス低減策	対策を実施する部門
需要予測	・食品加工、小売、飲食サービス
買物・献立管理	・家庭
倉庫整備（一部地域[*1]のみ）	・農畜水産、倉庫

*1: Africa, Middle East, Non-OECD America, Non-OECD Asia

対策費用として、POS 情報を用いた需要予測について、まず、2014 年の POS 普及率を、世界各地域の成人 10 万人あたり POS ターミナル数 [16)]を参考に、2%（Africa）～42%（OECD Americas）と推計した。さらに、小売、飲食サービスに関し、各地域の POS 普及率を 60%（米国で 2020 年代後半に予想される値）に引き上げる場合に必要な POS ターミナルの費用と、需要予測の費用を算定した。ここで、POS ターミナルの費用は、タブレット・周辺機器を利用する場合は 364 US$/個/yr[17)]、スマートフォンを利用する場合は 0 US$/個/yr とした。需要予測の費用は 491 US$/店舗/yr [18)]とした。また、POS 普及率が 60%まで上昇した場合の各地の食品ロス低減率を、POS 有無毎の推計ロス率を基に、表 3-2 のように想定した。

食品加工に関し、需要予測による食品ロス低減率は小売と同じとし、対策費用は、食品加工の廃棄費用低減×小売の単位廃棄費用低減当たり対策費用、より設定した。

家庭における買物・献立管理アプリは、スマートフォン等既存の端末機器で利用するとし、アプリの利用料のみ 9 US$/世帯/yr [19)]を計上した。これによる、家庭の食品ロス低減率は、米国で期待されている数値 [10)]や SDGs ターゲット 12.3 を参考に 50%とした。

倉庫整備について、文献 20)のコールドチェーン普及率（例えば果物・野菜の場合：先進地域 95%、 西アフリカ 10%、南アジア 10%、中南米 30%等）を参考に、コールドチェーン普及率が低い途上地域の普及率を先進地域並みに上げる場合の費用と、それによる食品ロス低減率を設定した。ここで、収穫後倉庫整備の費用には、果物野菜、穀物、イモ類、油糧種子、生乳、魚介類の生産量 [21)]に対して、追加的に必要な倉庫（0.008 US$/$m^3$/day ; コンテナ型収蔵倉庫 [22)]を参考に設定）と冷却機器・電気の費用を、流通倉庫は、倉庫自体はあるものの冷蔵設備が不十分なものに冷却機器・電気費用が必要になるとした。

表 3-2 対策による食品ロスの低減率（%）（乳製品の例）

	対策	倉庫整備		需要予測			買物・献立管理
	食品ロスが低減する部門	農畜水産(収穫後)	倉庫（流通）	食品加工	小売	飲食サービス	家庭
地域	Japan	−	−	48	48	28	50
	OECD Americas	−	−	30	30	27	50
	OECD Asia, Oceania	−	−	30	30	27	50
	OECD Europe	−	−	45	45	37	50
	Africa	67	67	58	58	12	50
	Middle East	24	25	56	56	39	50
	Non-OECD Americas	60	61	48	48	30	50
	Non-OECD Europe, Eurasia	−	−	53	53	44	50
	China	−	−	50	50	39	50
	Non-OECD Asia	64	67	56	56	25	50

分析には、食品ロス低減による世界各地域・各部門への影響波及を考慮するため、産業連関表（I-O 表）を用いる。I-O 表として、国際貿易分析プロジェクト（GTAP: Global Trade Analysis Project）のデータベース ver.10[23)]より 2014 年データを入手し、世界 10 地域毎に区分した。これを用いて、食品ロス低減による各地域・各産業部門の生産額変化を算定する。簡便のため、食品ロス低減に伴う価格の変化は考慮していない。また、食品ロス低減に伴い、例えば廃棄物由来の有機肥料が減少する場合に化学肥料で補う、といった代替補充も特に考慮していない。以下、食品ロスの低減を特に考慮しない場合を「基準ケース」、考慮する場合を「食品ロス低減ケース」と呼ぶ。

食品ロス低減による最終エネルギー消費量の変化は、基準ケースの石炭・石油、電力・熱、ガスの各エネルギー消費量[24)]に、食品ロス低減による石炭・石油製品、電力・熱供給、ガスの各部門の生産額変化率を乗じて推計した。途上国の家庭では、調理用エネルギーにバイオマス利用も少なくない[24),25)]ことより、家庭部門の木材製品の投入変化率を基にバイオエネルギー消費量変化も考慮した。

GHG 排出量の変化は、基準ケースにおける、燃料燃焼 CO_2、工業プロセス CO_2、エネルギー関連 CH_4、農業 CH_4・N_2O、廃棄物 CH_4、工業プロセス N_2O、農業 N_2O、その他 N_2O（以上は文献 25)）、及び土地関連 CO_2 [21)]の各排出量に対し、主な関連部門（表 3-3）の生産額変化率を乗じて推計した。

表 3-3 エネルギー消費・GHG 排出に関連する主な部門

GTAP10の65部門		Energy-coal/oil	Energy-gas/heat	Energy-ele	Energy-Biofuels/waste	CO_2-Energy(Direct)	CO_2-Energy(Indirect)	CO_2-non Energy	CH - Energy	CH - Agriculture	CH - Waste	N_2O - Ind. processes	N_2O - Agriculture	N_2O - Other	Lnad-use change
1	Paddy rice									x			x		x
2	Wheat												x		x
3	Cereal grains nec												x		x
4	Vegetables, fruit, nuts												x		x
5	Oil seeds												x		x
6	Sugar cane, sugar beet												x		x
7	Plant-based fibers														x
8	Crops nec														x
9	Bovine cattle, sheep and goats									x			x		
10	Animal products nec												x		
11	Raw milk									x			x		
12	Wool, silk-worm cocoons									x			x		
13	Forestry														
14	Fishing														
15	Coal								x						
16	Oil								x						
17	Gas								x						
18	Minerals nec														
19	Bovine meat products														
20	Meat products nec														
21	Vegetable oils and fats														
22	Dairy products														
23	Processed rice														
24	Sugar														
25	Food products nec														
26	Beverages and tobacco products														
27	Textiles														
28	Wearing apparel														
29	Leather products														
30	Wood products				x										
31	Paper products, publishing														
32	Petroleum, coal products	x				x									
33	Chemical products							x				x			
34	Basic pharmaceutical products														
35	Rubber and plastic products														
36	Mineral products nec							x							
37	Ferrous metals														
38	Metals nec														
39	Metal products														
40	Computer, electronic and optic														
41	Electrical equipment														
42	Machinery and equipment nec														
43	Motor vehicles and parts														
44	Transport equipment nec														
45	Manufactures nec														
46	Electricity			x			x								
47	Gas manufacture, distribution		x			x									
48	Water										x			x	
49	Construction														
50	Trade														
51	Accommodation, Food and servic														
52	Transport nec														
53	Water transport														
54	Air transport														
55	Warehousing and support activi														
56	Communication														
57	Financial services nec														
58	Insurance														
59	Real estate activities														
60	Business services nec														
61	Recreational and other service														
62	Public Administration and defe														
63	Education														
64	Human health and social work a														
65	Dwellings														

注）文献 26)を参考に設定。

3.3 分析結果

図 3-2 に、アフリカで倉庫整備により食品ロスを低減した場合の各部門の生産額変化を示す。収穫後倉庫、流通倉庫において冷却機器と電力が追加的に必要と想定したため、電気機器や電力・熱供給部門で生産が増大すると分析された。但し、耕種農業、畜産・水産、食品加工をはじめ、化学製品、石炭・石油製品等多くの部門では生産額が減少する。これらの部門では、食品ロスに体化されていた生産活動が節減されるといえ

る。また、大半の影響はアフリカで生じるが、化学製品は OECD Europe や China 等、輸入先各地域での節減にも寄与すると分析された。

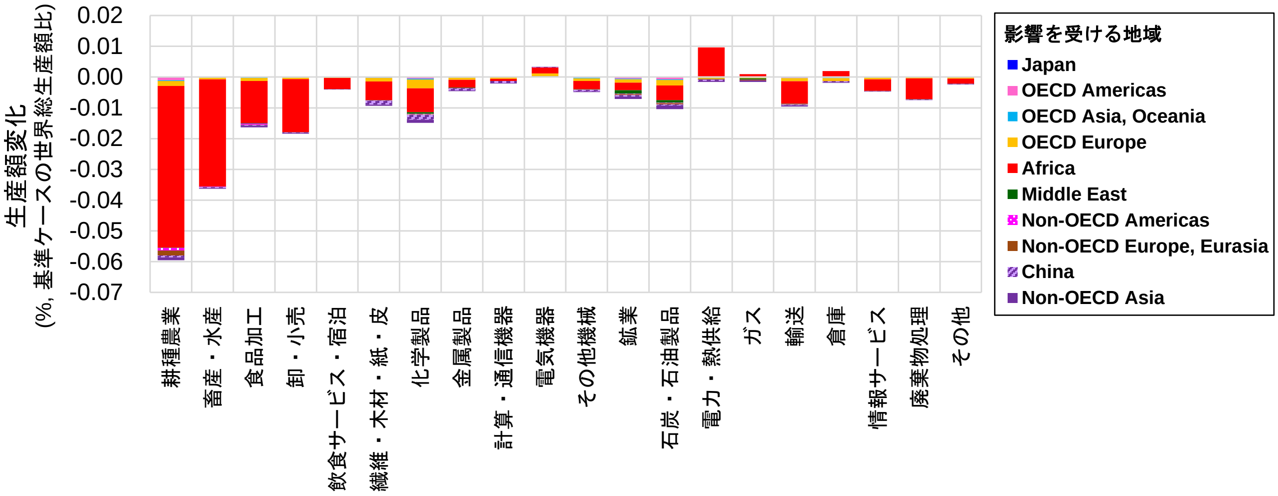


図 3-2 アフリカで倉庫整備により食品ロスを低減した場合の部門別生産額変化

注）産業 65 部門別に分析した結果を 20 部門に集約して表示。

世界の全地域で倉庫整備、需要予測、家庭の買物・献立管理により食品ロスを低減した場合は図 3-3 に示すように、計算・通信機器、情報サービス業の生産活動は、世界全体で 1%程増大する。一方、廃棄物処理は 7%、農畜水産、食品加工は 5～6%、化学製品は 1%、金属製品は 0.5%、石炭・石油製品、電力・熱供給、ガスは 1～2%節減される、と分析された。

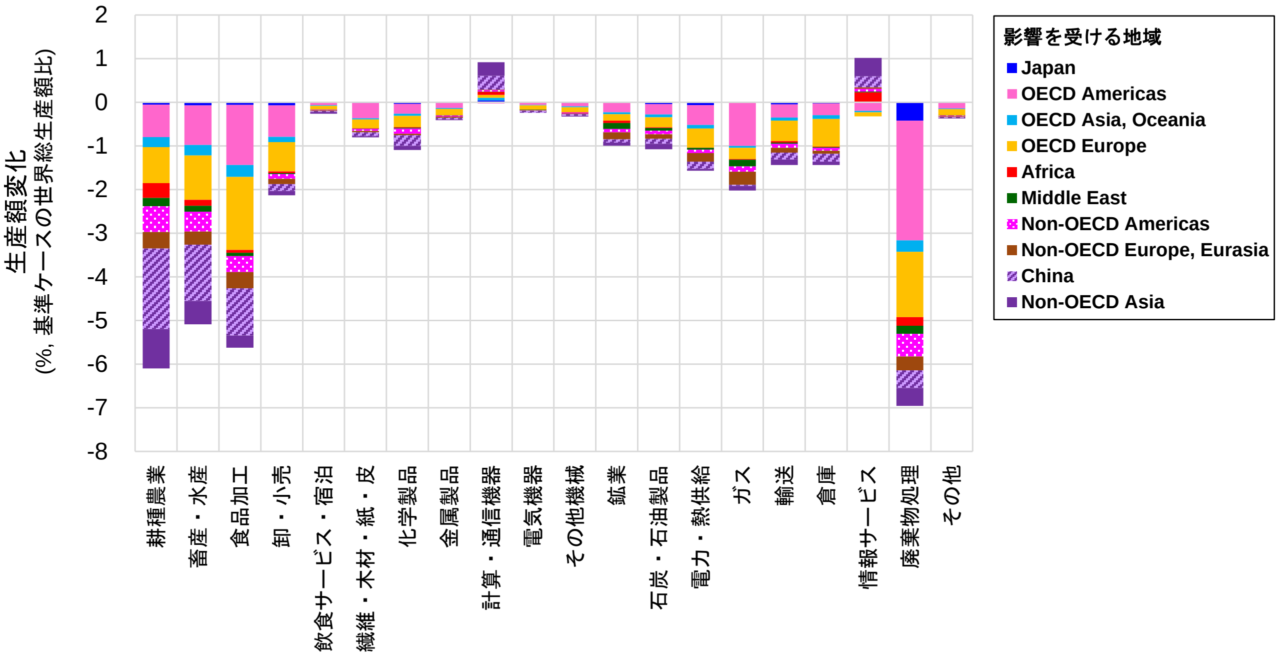


図 3-3 世界の全地域で想定した想定した全対策により食品ロスを低減した場合の部門別生産額変化

注）産業 65 部門別に分析した結果を 20 部門に集約して表示。

世界の全地域で想定した全対策により食品ロスを低減した場合の、各地域のエネルギー消費量変化を図 3-4 (a) に示す。OECD Americas で 1.7 EJ/yr、OECD Europe や China で 1 EJ/yr、世界全体で 6.3 EJ/yr（基準ケースの最終エネルギー消費量の 1.6%）の省エネルギーに寄与すると算定された。

GHG 排出量（図 3-4(b)）は、世界全体で 11 億 tCO_2 eq/yr（基準ケースの GHG 排出量の 2.1%）の削減に寄与すると算定された。どの地域も燃料燃焼 CO_2 の他、CH_4、N_2O 等の排出が削減される。さらに、Non-OECD Americas、Non-OECD Asia、Africa では、食品ロスに体化された農作物生産が節減されるに伴い、耕地拡大による土地関連 CO_2 排出も抑制される。このように、多岐にわたり、省エネルギー、GHG 排出削減に寄与すると考えられる。

なお、世界全体で 11 億 tCO_2 eq/yr の削減という数字は、対象年他、各種想定が異なるため比較は出来ないが、FAO の 2011 年を対象にした分析で、食品ロス低減により 14 億 tCO_2 eq/yr 削減されるという結果 [27] と、オーダー的に同程度の値となっている。

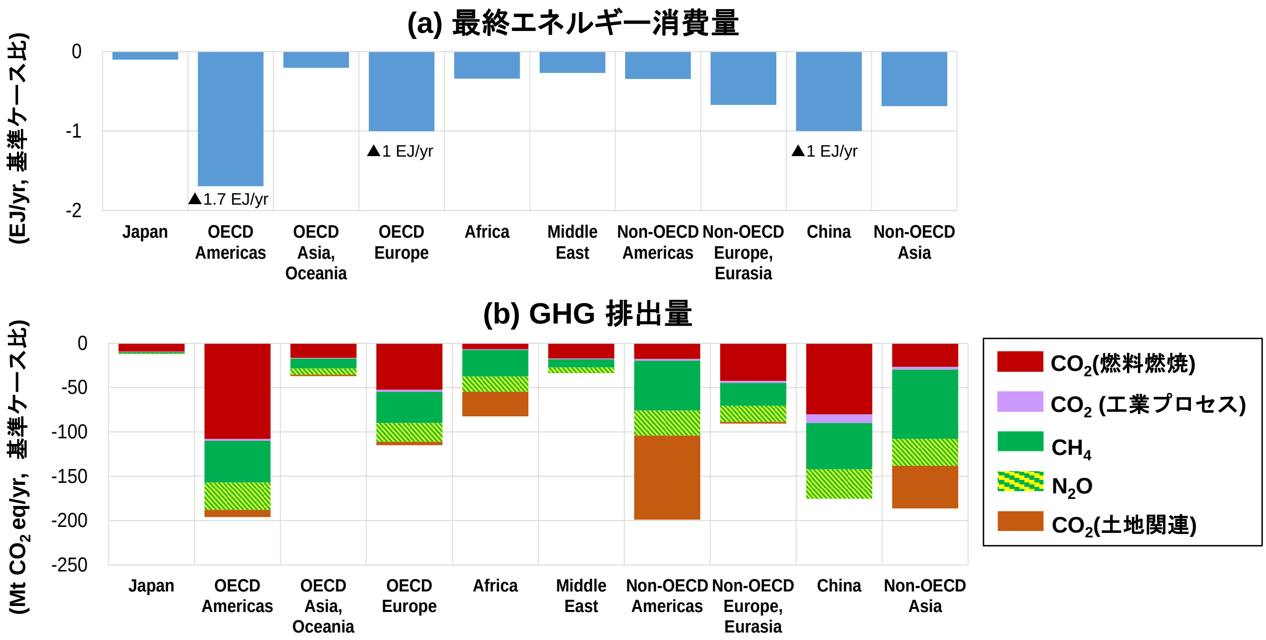


図 3-4 世界の全地域で倉庫整備、需要予測、家庭の買物・献立管理により食品ロスを低減した場合の地域別(a)最終エネルギー消費量と(b)GHG 排出量の変化

参考までに、各地域の食品ロス低減策について、対策を行う部門の、追加費用（情報機器、アプリ利用料等）と食品ロス低減に伴う材料や廃棄物処理などの投入減少の合計を「食品ロス低減の正味費用」として算出した。さらに、それを「世界全体の GHG 削減量」で除し、「世界平均 GHG 削減費用」として算出した。表 3-4 に、世界平均 GHG 削減費用が安価と算定された順に示す。

これより、次のような傾向が読み取れる。想定した対策のほとんどは、正味費用が負、すなわち便益が生じると算定される。中でも、Middle East での倉庫整備は、世界平均 GHG 削減費用が最も安価な対策と推計された。これは収穫後や流通の倉庫整備により主に同地域の農業 CH_4、N_2O が削減されることによるが、GHG 削減量は限られる。続いて、買物・献立管理アプリを活用した家庭の食品ロス低減は、世界のどの地域で実施した場合も、比較的安価な GHG 排出削減策と評価される。対策に特別な機器追加の必要が無く、アプリ費用のみを想定したことに加え、食品ロス低減の影響がサプライチェーンの上流に向け広く及ぶことが要因と考えられる。ただ、日本の家庭のみで食品ロスを低減した場合、海外への影響波及を考慮しても▲7 百万 tCO_2 eq/yr に留まる。家庭の食品ロス率が高いとされる OECD Americas、China をはじめ、全地域の家庭で食品ロスを半減した場合は▲7 億 tCO_2 eq/yr に寄与すると考えられる。

需要予測による食品業（飲食サービス・小売・食品加工）での食品ロス低減に伴う世界の GHG 削減量は、家庭での食品ロス低減に伴う GHG 削減量程大きくないものの、世界全体で実施した場合▲3 億 tCO_2 eq/yr GHG 排出削減に寄与すると考えられる。Non-OECD Asia、Africa で実施する場合 GHG 削減費用が正となったが、これは、同地

域の POS の導入率がいずれも 2%と低く、これを 60%までに引き上げる費用が必要と想定したことによる。

表 3-4 食品ロス低減策別の世界の GHG 削減量と世界平均 GHG 削減費用

食品ロスを低減する地域	食品ロス低減策	世界平均 GHG削減費用 (US$/t CO_2eq)	世界の GHG削減量 ($MtCO_2$eq)
Middle East	倉庫整備	-276	1
OECD Europe	買物・献立管理	-165	99
Japan	買物・献立管理	-157	7
OECD Europe	需要予測	-151	56
Japan	需要予測	-128	9
OECD Americas	買物・献立管理	-123	165
OECD Americas	需要予測	-119	46
OECD Asia, Oceania	買物・献立管理	-104	32
OECD Asia, Oceania	需要予測	-101	12
Non-OECD Europe, Eurasia	買物・献立管理	-71	61
China	買物・献立管理	-65	126
Middle East	買物・献立管理	-56	25
Non-OECD Europe, Eurasia	需要予測	-52	25
Africa	倉庫整備	-44	15
China	需要予測	-44	59
Non-OECD Asia	倉庫整備	-44	45
Non-OECD Americas	買物・献立管理	-41	69
Middle East	需要予測	-37	8
Non-OECD Americas	倉庫整備	-32	43
Non-OECD Asia	買物・献立管理	-28	71
Africa	買物・献立管理	-23	38
Non-OECD Americas	需要予測	-23	55
Non-OECD Asia	需要予測	37	45
Africa	需要予測	55	17

Non-OECD Americas、Non-OECD Asia、Africa の倉庫整備による食品ロス低減も、投入原料の節約という便益をもたらしながら、▲1 億 tCO_2 eq/yr に寄与すると算定された。

このように、食品ロスの低減は、家庭や食品業に便益をもたらすと同時に、世界全体で 11 億 tCO_2 eq/yr 程度の GHG 排出削減に寄与する可能性が考えられる。これまで家庭や食品業で食品ロスが発生している背景には、3.1 節で述べたように、家にある食材の期限や量を忘れる/知らないため二重に購入する、又、食品業が販売機会を失わないように多めに発注や生産を行う等の状況があげられる。今回想定した買物・献立アプリや需要予測による食品ロス低減の実行性には不確実性があり、さらなる精査が必要であるが、情報技術の活用によって上述した状況が改善され、食品ロスが低減するとすれば、GHG 排出削減の観点からも、有効な対策と期待される。

3.4 まとめと今後の課題

世界的に導入され食品ロス低減に寄与する可能性が考えられるものとして、POS 情報を用いた需要予測、家庭における買物・献立アプリの活用、及びこれらの活用に向け一部途上地域で必要な収穫後・流通倉庫の整備を取り上げた。そして、これら対策による食品ロス低減が、世界の各地域各部門の生産、エネルギー消費、GHG 排出に及ぼす影響を分析した。分析対象年は 2014 年で、GTAP10 の I-O 表他、各種関連データを用いた。主な結果は、以下のようにまとめられる。

- 想定した対策が全て実施され世界の食品ロスが低減した場合、計算・通信機器、情報サービス業は、世界全体で生産が 1%程増大する。一方、廃棄物処理は 7%、農畜水産業、食品加工は 5～6%、化学製品は 1%、金属製品は 0.5%、石炭・石油製品、電力・熱供給、ガスの各部門では 1～2%、節減される。
- その結果、世界全体で、最終エネルギー消費量は食品ロス低減を想定しない場合に比べ 6.3 EJ/yr（1.6%）、GHG 排出量は 11 億 t CO_2 eq/yr（2.1%）削減される。すなわち、食品ロス低減の影響は多くの部門に波及し、これまで食品ロスに体化されていたエネルギー、GHG の削減、及び省物質化に寄与すると考えられる。
- 食品ロス低減を行う部門の、追加費用（情報機器、アプリ利用料等）と食品ロス低減に伴う材料や廃棄物処理などの投入減少額を「食品ロス低減の正味費用」とすると、ここで想定した対策のほとんどは、追加費用より投入減少額の方が大きく、正味費用は負と算定される。
- このような手頃な費用で、食品ロス低減が促進されるとすれば、情報技術の活用は、温暖化緩和、そして省資源化の観点からも、有望な対策と期待される。

なお、対策費用や対策による食品ロス低減率の設定については、各種実証データの充実に留意しつつ、引き続き精査・改善が必要である。また、情報化と消費者ニーズの多様化に伴い、食品のオンライン販売も今後拡大すると見込まれる。その際に考えられる食品ロス低減策や影響についても、調査・検討が必要である。さらに、長期的な構造変化を考慮した生産・サービス、エネルギーの需要シナリオ策定という点では、今世紀中頃までの食料需要増大、技術進展を踏まえた分析が必要であり、今後の課題である。

参考文献（第 3 章に関するもの）

1) FAO; Energy–smart food for people and climate, (2011). http://www.fao.org/3/i2454e/i2454e00.pdf (ｱｸｾｽ日 2019.1.12)
2) IPCC; Climate Change and Land (2019)
3) FAO; Global food losses and food wastage: extent, causes and prevention. FAO, Rome (2011)
4) UN; Sustainable Development Goals, https://sustainabledevelopment.un.org/?menu=1300 (accessed 2019.10.10)

5) 農林水産省; 食品リサイクル法の基本方針改正案等について　資料 4, https://www.maff.go.jp/j/council/seisaku/syokusan/recycle/h31_1/attach/pdf/index-15.pdf (ｱｸｾｽ日 2021.9.28)
6) African Union Commission; Malabo Declaration on Accelerated Agricultural Growth and Transformation for Shared Prosperity and Improved Livelihoods (2014)
7) A. Grubler et al., A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. nature energy, 3(6) (2018), 515-527.
8) D. P. van Vuuren et al.; Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies, Nat. Clim. Change, (2018), 391-397.
9) F. Creutzig, L. Niamir, X. Bai, M. Callaghan, J. Cullen, et al.; Demand-side solutions to climate change mitigation consistent with high levels of well-being, Nature Climate Change, 12(1) (2022), 36-46.
10) ReFED; Explore solutions to food waste, https://insights-engine.refed.org/solution-database?dataView=total&indicator=us-dollars-profit　(ｱｸｾｽ日 2021.10.10)
11) 経済産業省；食品ロス削減に向けた経済産業省の取組 (2017), https://www.caa.go.jp/policies/policy/consumer_policy/information/food_loss/conference/pdf/adjustments_index_10_170915_0006.pdf　(ｱｸｾｽ日 2018.10.2)
12) Symphony Retail; CPG Shelf Planning, https://www.symphonyretailai.com/cpg/shelf-planning/　(ｱｸｾｽ日 2021.10.3)
13) App Store; pecco - 冷蔵庫レシピ献立料理アプリ (ｱｸｾｽ日 2021.10.8)
14) B. Bajželj et al.; The role of reducing food waste for resilient food systems,　Ecosystem Services, 45 (2020) 101140
15) T. Stathers et al.; A scoping review of interventions for crop postharvest loss reduction in sub-Saharan Africa and South Asia, Nature Sustainability, 3, 821–835 (2020)
16) World Bank; Data Bank, POS terminals per 100,000 adults
17) 林礼美, 本間隆嗣, 秋元圭吾; 情報技術等の活用による日本の食品廃棄低減が各部門のエネルギー消費と GHG 排出に及ぼす影響：産業連関表を用いた分析，エネルギー・資源, 41-3, 87-97 (2020).
18) Ginesys; Ginesys Subscription Pricing, https://www.ginesys.in/pricing　(ｱｸｾｽ日 2021.10.5)
19) Cookpad dining; クックパッドダイニングプラン, https://cookpad.com/dining/about/360　(ｱｸｾｽ日 2021.9.20)
20) Food Waste Reduction & Cold Chain Technologies; Assessing the potential of the cold chain sector to reduce GHG emissions through food loss and waste reduction, (2015), https://www.corporate.carrier.com/Images/Global-Food-Cold-Chain-GHG-Emissions-Study_v2_tcm558-77711.pdf　(ｱｸｾｽ日 2021.9.27)
21) FAO; FAOSTAT data, https://www.fao.org/faostat/en/#data
22) Jiji; Sell faster buy, smarter, https://jiji.ng/301-containers (ｱｸｾｽ日 2021.10.13)
23) GTAP; GTAP 10 Data Base, https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx,　(ｱｸｾｽ日 2021.9.15)
24) IEA; World energy balances 2019 edition (2019)
25) IEA; CO_2 emissions from fuel combustion 2019 edition (2019)

26) Z. B. Irfanoglu, D. van der Mensbrugghe; Development of the version 9 non-CO_2 GHG database (2015), p.34, https://www.gtap.agecon.purdue.edu/resources/download/7813.pdf (ｱｸｾｽ日 2020.8.20)

27) FAO; Food wastage footprint & Climate Change (2015), Rome, 4 pp. http://www.fao.org/3/a-bb144e.pdf (ｱｸｾｽ日 2019.11.17)

第4章　アパレルロスの低減とライフスタイル変化

アパレルは、製造から廃棄に至るまでのエネルギー消費量やライフサイクルの短さなどから、環境負荷が高いとの指摘がなされている。例えば、国連はファッション産業が世界の温室効果ガス排出量の 10%を占めているとしている [1]。また、服の 50%程度は着られることなく、廃棄されているとされているし、多くの服は稼働率が低く、クローゼットで出番を待っているとも言われる。本章では、アパレルロスの低減やアパレル関連のライフスタイル変化について、文献 2, 3)を中心に整理するとともに、シナリオ分析の可能性について検討を行った。

4.1　ファッション産業のエネルギー消費・CO_2 排出評価

Niinimäki et al.は、地球環境に対してファッション産業は次のような 5 つの問題点を有すると指摘する [4]。ファッション産業は世界の CO_2 排出量の 8-10%（年間 40～50 億トン）を占め、水を大量消費（年間 79 兆リットル）し、繊維加工や染色による工業用水汚染の約 20%の原因となっている上、海洋マイクロプラスチック汚染の約 35%（年間 19 万トン）を占め、新品の売れ残り製品を含めて不要になったアパレル商品は膨大な量の繊維廃棄物（年間 9200 万トン以上）となり、その多くは埋め立てや焼却処分される。

ファッション産業は、繊維や糸、テキスタイルの生産工程における水や化学物質の使用、衣服の製造、流通、消費過程における CO_2 排出など、サプライチェーンのあらゆる段階で環境に影響を与えている（図 4-1）。

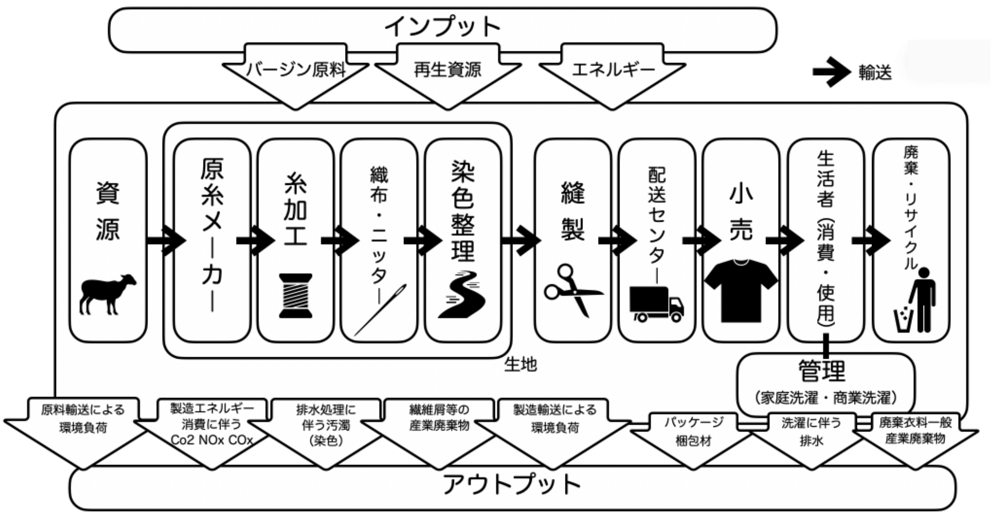


図 4-1　衣料品のライフサイクルと環境負荷の概念図

（出典：田村・稲葉・山口・佐藤 [5]を元に作成）

ファッション消費に伴うエネルギー消費と CO_2 排出量は、主に原料の繊維製造と衣料品が消費者の手に渡った後の洗濯やアイロンがけなどの使用段階、および航空輸送を使用する場合の輸送の際に発生する。しかし、ファッション産業の環境負荷を正確に評価することは原材料の繊維生産段階からアセスメントしなければならない上に、衣服生産のグローバル化が進んだことからも、正確な評価は極めて困難になっている。例えばウールなどの動物由来の繊維は、家畜が排出する温室効果ガスなども考慮に入れる必要があり、ウール生産が環境に与える影響を数値化することは難しい。さらに、ファッション消費に伴うカーボンフットプリントは、各国で使用されるエネルギーの供給源の影響を受ける。例えば、石炭ベースのエネルギーに依存する中国は、ヨーロッパで製造された繊維製品よりも40%程度大きなカーボンフットプリントとなる[6)]。また、中国産の T シャツとジーンズをスウェーデン人が使用した場合、スウェーデンでは衣類を洗濯・乾燥するためのエネルギーのほとんどが原子力発電で賄われるため、ファッション消費における CO_2 排出量は中国での衣料品生産によるものが全体の 71%を占める。その一方で、一般的なヨーロッパの洗濯機は衣類の素材別に洗う温度が設定されており、綿、リネン、合成繊維、混紡などは 30-40℃、ジーンズは 40℃、リネンなどを殺菌する場合は 90℃の熱湯で洗濯するため、高温で洗濯する際にはエネルギー消費は比例して高くなってしまう。

2011 年の Carbon Trust のデータによると、ヨーロッパの家庭における衣料品の使用（洗濯、乾燥、アイロンなど）に伴う CO_2 排出は年間 5 億 3,000 万トンであると概算されている [7)]。衣料品の使用方法や同じ衣服を何回着るのかという維持管理は消費者個人の選択に依存するため概算しかできないが、Carbon Trust によると平均的な T シャツの着用と管理に伴う CO_2 排出量は、T シャツ 1 枚のライフサイクルにおける排出量の半分を占めている。例えば、綿の T シャツのライフサイクル排出量を試算すると、50 回洗濯した場合、CO_2 排出量の 35%は繊維生産に起因し、52%は使用段階で発生することが判明している。しかし、T シャツ 1 枚の管理方法も繊維の種類によって異なるため、ポリエステルの T シャツとコットンの T シャツでは排出量は異なる。また、天然繊維は石油原料の合成繊維に比べて生地の生産段階における CO_2 排出量は少ないが、天然繊維は合成繊維に比べて洗濯、乾燥、アイロンがけに必要なエネルギーが大きいため、生産時の低カーボンフットプリントは、使用段階で相殺される可能性がある。

4.2 ファストファッションの大量生産・大量消費モデル

近年、アパレルの売り上げは飛躍的に伸びており、その背景にあるのがファストファッションの台頭である。ファストファッションとは、1990 年代後半から 2000 年代前半にかけて登場した衣料販売チェーンの業態のことを差し、その特徴は短いサイクルで流行のデザインを追いながら衣料品を大量生産し、低価格で販売することによって消費者に大量消費を促すというものである。

ファストファッションでは、「計画的旧式化（planned obsolescence）」という、次々と新しい商品を投入することによって意図的に商品の寿命を短く設定し、消費者に商品を購入させ続ける手法を用いている。アパレル企業において衣服のコレクション発表

の回数は、慣習的に年間春と秋の 2 シーズンであったが、ファストファッションの場合は有名ブランドが発表した服のデザインを模倣し、数週間で商品化するという生産工程の迅速さから、新コレクションの発表はより頻度が高い。ファストファッションは上述の計画的旧式化によって寿命が短く安価なため、消費者は安価な衣料品を「ほぼ使い捨て」の生鮮品と見なし、7～8 回着ただけで捨ててしまう傾向が強くなっている [8)]。加えて、使用済みファストファッションの製品は市場価値がほとんど無くなり、セカンドハンド製品を扱うサービスも原則引き取らないため、リサイクルすることは難しい。

衣類の年間生産枚数は 2000 年から倍増し、2014 年には初めて 1000 億枚を突破した。これは年間 1 人当たり約 14 着の衣料品が生産されている計算となり、一人当たりの衣料品購入数は約 60%増加した [9)]。世界中でアパレル商品の売上高は伸びているが、特にブラジル、中国、インド、メキシコ、ロシアなどの新興国 5 カ国では、衣料品の売上がカナダ、ドイツ、イギリス、アメリカなどと比較して 8 倍の速さで伸びている。アパレル産業の環境効率が向上しないまま新興国の人々が欧米並みの衣料品消費レベルに達した場合、アパレル産業の環境フットプリントはより大きくなることが予想されている。

4.3　ファッション廃棄の問題

不要になった衣料品を、ペットボトルのように新しい商品へ再生することができるようにすることが理想的であるが、現在の技術では使用済み衣料品を原材料となる繊維まで確実に戻すことは困難であるとされている。シュレッダーや化学分解などのリサイクル技術も未だ発展途上にある上、衣類をリサイクルすることで得られるはずの素材量を吸収できるほど大きな市場も存在していないのが現状である。その結果、毎年 5 着の衣服が生産されるごとに、3 着が埋立地や焼却場に運ばれていると言われている。ドイツは、使用済み衣類のほぼ 4 分の 3 を回収し、その半分を再利用、4 分の 1 をリサイクルしており、ほとんどの国より優れたリサイクル・システムを有している。他の国々における回収率ははるかに低く、米国では 15%、日本では 12%、中国では 10%となっている [9)]。

高田と田原による日本の繊維製品のリサイクル率に関するデータでは、紙およびプラスチックのリサイクル率が約 60%、スチール缶およびアルミ缶が約 90%であるのに対し、毎年約 200 万トンに達する使用済み繊維製品の内、リサイクルされる率は約 11%に留まると試算されている [10)]。その理由としては次の 3 点があげられている。1 つ目は、ファッション性を有する製品であるために商品展開が幅広く、同種の製品を一定規模以上回収することが難しいこと、2 つ目は、素材の複合度が高いため個々の素材に分離・分解することが難しいこと、3 つ目は、再商品化してもその用途の拡大が見込めなかったりすることである。また、高田と田原は日本で毎年約 200 万トンに達する使用済み繊維製品が発生している理由として、衣料品の生産流通構造が多層構造であるために各階層で廃棄物や在庫品が発生することや、衣類の低価格化が進んだことによって製品の使い捨て傾向が強まったこと、そして流行や着る人の体型の変化等によって製品はその寿命を待たずして廃棄されること、などをあげている。

また、ファッション業界全体で見ると、平均的な売れ残り在庫は 17-20%であると Harvard Business Review は見積もっている[11]。McKinsey & Company は、購入した衣類の 60%がわずか 1 年で捨てられるとも推定している[9]。また、イギリスの保険会社の推計によると、2005 年には価格にして 73 億 9,000 万英ポンド相当の衣類がイギリスにおいて一度も使用されずに捨てられていることが判明している。これは、2005 年の国民総支出の 19%に相当する[12]。このようなことが起きている理由としては、ファストファッションの製品が安価であることから消費者が不要な衣服まで買ってしまうことや、e コマースの流行で試着をせずにサイズやイメージと合わない衣服を買ってしまうことなどがあげられる。

4.4 対応の状況と展望

ファッション業界も非難の矛先が向けられていることを認識しており、多くの女性ファッション誌では毎号で「エシカル」「サステナ」というキーワードが必ずどこかに登場し、エシカル（倫理的)、あるいはサステナビリティ（持続可能性）を謳う商品を紹介する特集ページが組まれている。しかし、当然ながら、ファストファッションの価格帯より何倍も高いため、たとえ環境に配慮された商品であっても、社会に浸透してファッション産業がもたらす環境負荷を軽減させることができるほどの影響力を持つことはあまり期待できないか、結果が出るまでには長い時間がかかると考えられる。

また、衣料品の廃棄やリサイクルは消費者の手に委ねられている部分も多いため、仮に消費者が環境に配慮した生分解可能なヴィーガン・レザーの靴を購入しても、一定期間使用した後に可燃ゴミとして捨ててしまった場合、一般の廃棄物（ファッション・ロス）と同じになってしまう。消費者の購買行動を今すぐ転換させることは困難であるため、ファッション・ロスを削減するためにはシステム的な変革が必要である。生産・消費・廃棄の各段階でエネルギー消費やファッション・ロスを減らすいくつかの取り組みの事例を記載する。

(1) 生産段階

生産段階でエネルギー消費やファッション・ロスを減らすには、まずは現行のリニアなライフサイクルを、デザイン段階からサーキュラーなシステムに転換させる必要がある。ECAP（European Clothing Action Plan）は循環型衣服システムを導入するための対策を提案し、サーキュラー・ファッションを次のように図式する（図 4-2)。

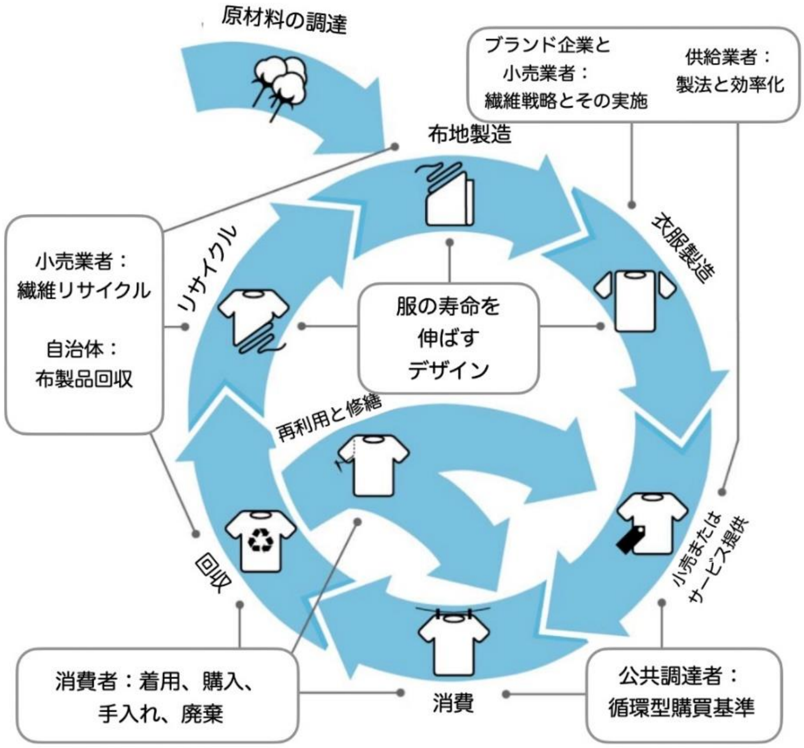


図 4-2　サーキュラー・ファッションの概念図

（出典：Gray[8]を元に作成）

このサーキュラー・ファッションの概念図では、まずデザインの段階で使い捨てにならないような丈夫なもの、全季節型のもの、単一素材を使うなどしてリサイクルしやすいものを生産することを提案している。

アパレル CAD（Computer Aided Design System）を利用して余白の少ないパターンを作成し工場から廃棄される生地の量を最小限に留めることや、3DCAD を使用し、縫製を行う前に立体のデジタル・モデルで製品の完成状態を確認することによってサンプルの作成や輸送にかかる環境負荷をほとんどゼロにするなどの取り組みがなされている。また、縫製のオートメーションを進めることによって、オンデマンド生産を可能にしたり、カスタマイズによって付加価値を付与することによって、生産段階で廃棄量を減少させることも可能である。縫製のオートメーションは、アスレジャーの業界で流行しているシームレス・レギンス（縫い目のないレギンス）やニットドレスなどの生産でフル・オートメーションが可能になっている。また、AI デザイナーも開発中されてきており、流行の分析によって自動的にデザインを作成したり、消費者が自由に衣服のカスタマイズをすることを AI デザイナーが手助けするようになることが予測されている[13]。

(2) 消費段階

近年、シェアリング・サービスやサブスクリプション・サービスが様々な業態で提供されているが、ファッション業界でもそのトレンドは拡大傾向にある。また e コマースの成長によって実店舗を持たないブランドも増えてきており、この傾向は今後も続くと予測されている（図 4-3）。

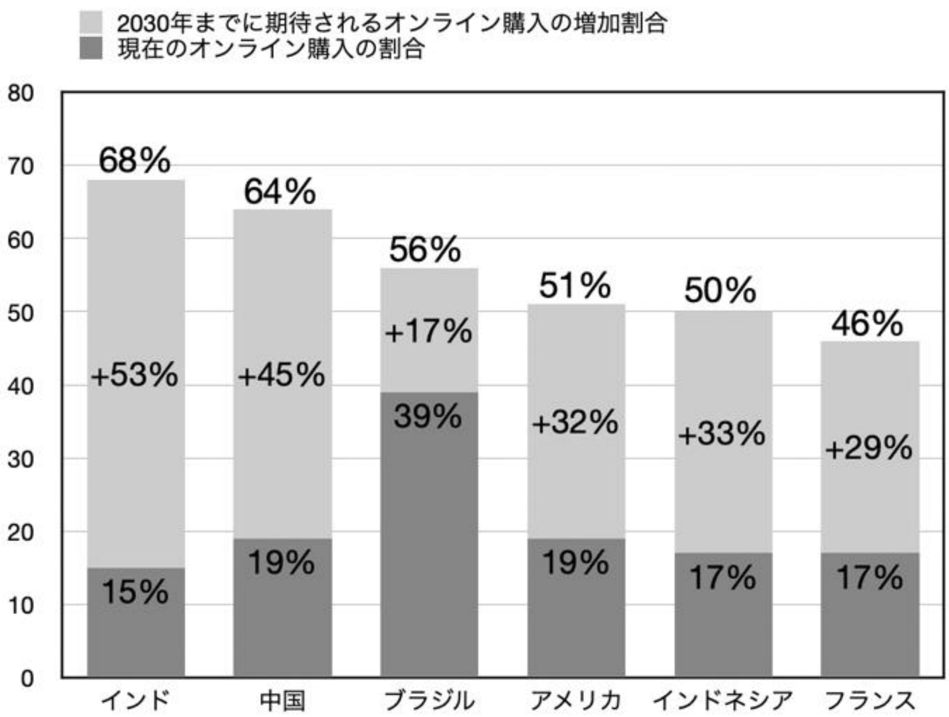


図 4-3　増加する衣料品のオンライン購入

（出典：Deloitte[14]を元に作成）

E コマースでの販売によって、ブランド企業は実店舗を維持することによるエネルギー消費や在庫を抱える必要がない。しかし、上述したように試着をせずに e コマースを通して衣服を購入してしまうと、サイズが合わなかったり、イメージが違っていたりするため、未使用で捨てられる服を増やしてしまうという側面がある。そのような問題を解決する方法としてバーチャル・フィッティングや体型を自動的に計測する技術などが開発されている。このように正確に体型を測定できるため、消費者はその測定値を参考に、自分の体型にフィットする服をオンラインで購入することができる。

(3) 廃棄段階

2018 年に EU は循環型経済包括提案（circular economy package）を欧州議会で採択し、これによって遅くとも 2025 年までにすべての EU 加盟国で繊維製品の分別収集を徹底させることが決定している。また、欧州議会はすでに衣類・繊維製品に対するエコ

ラベルの認証制度も導入している。その審査基準は厳格で、例えば人体や環境に有害な物質の使用制限、水質・大気汚染をもたらす度合い、衣類の寿命を延ばすための基準（洗濯・乾燥時の縮みにくさ、摩擦・光の照射に対する耐色性）などが細かく設定されている[15)]。加えて、EU 諸国の企業によっては、自主的にカーボン・フットプリントを製品表示する取り組みも行われている。

欧州議会の包括提案のように、日本でも繊維製品の分別収集が開始されたならば、ビン、缶、ペットボトルなどと同様に衣服や繊維製品を資源ゴミとしてリサイクルに回すことができるかもしれない。実際、自治体によってはすでに拠点回収などを実施している市町村もある。しかしながら、衣料品は複数の素材が組み合わせられているため、回収した後のリサイクルは容易ではない。例えばワンピース 1 着にしても、布地のコットンとプラスチック製のボタンや金属製のジッパーは分けておかなければリサイクルできないだろう。複数のマテリアルを使用する衣料品のリサイクルを考えるならば、原材料のデータを持つメーカーによる衣料品回収が理想的であろう。店舗における衣料品回収を実施したり、ダウンジャケットを集めてリサイクル・ダウンを使用したジャケットを生産するなどの活動も行われてきている。

なお、インターネットオークションの進展による中古服等の取引は、事実上の服のシェアリングの進展にあたるものであり、需給のマッチングを促し、アパレル製品の稼働率の向上、廃棄の低減となる。

4.5　まとめと今後の定量的な分析の展望

本章では、アパレル関連の LCA でのエネルギー消費、CO_2 排出の動向、また、排出削減に向けた可能性やファッション業界の取り組みの動向について整理を行った。今後の定量的な分析としては、第 3 章記載の食品ロスのように、産業連関表を用いて、部門横断的なエネルギー消費の低下の推計が考えられる。その上で、主要なエネルギー低下の可能性について、DNE21+モデルのような技術積み上げ型の世界エネルギーシステムモデルにおいてモデル化し、エネルギー供給側対策と一体的に分析、評価をすることが考えられる。

参考文献（第 4 節に関するもの）

1) United Nations Climate Change: https://unfccc.int/news/un-helps-fashion-industry-shift-to-low-carbon (アクセス日 2021.12.10)
2) RITE、FY2021 ALPS 報告書 (2022)
3) 木谷佳楠、秋元圭吾：ファッション消費に伴うエネルギー消費・CO2 排出評価、第 38 回エネルギーシステム・経済・環境コンファレンス 20-5（2021）
4) Kirsi Niinimäki, Greg Peters, Helena Dahlbo, Patsy Perry, Timo Rissanen and Alison Gwilt: The environmental price of fast fashion, Nature Reviews Earth & Environment, 1 (2020), pp.189-200.
5) 田村照子、稲葉敦、山口庸子、佐藤真理子：低環境負荷型ファッション文化に関する研究、服飾文化共同研究報告 (2010)、pp.1-8.

6) Laili Wang, Yi Li, Wanwen He: The energy footprint of China's textile industry: Perspectives from decoupling and decomposition analysis, Energies, 10-1461 (2017), pp.1-11.
7) Glen Peters, Chris Webber, Jan Minx and Peter Grace; International carbon flows: Clothing, Carbon Trust (2011), pp.1-17.
8) Sarah Gray: Mapping clothing impacts in Europe: the environmental cost, European Clothing Action Plan (2017), pp.1-41.
9) McKinsey & Company: https://www.mckinsey.com/ business-functions/sustainability/our-insights/ style-thats-sustainable-a-new-fast-fashion-formula (アクセス日 2021.12.10).
10) 高田亜佐子、田原聖隆；衣類におけるライフサイクルアセスメントの現状と課題、廃棄物資源循環学会誌、21-3 (2010)、pp.148-156.
11) Harvard Business Review: Harvard Business Review on managing supply chains (2011) , pp.　1-205.
12) Statista, Consumer expenditure on clothing in the United Kingdom (UK) 2005-2020: https://www.statista.com/statistics/289999/consumer-spending-on-clothing-in-the-united-kingdom-uk/ (アクセス日 2021.12.1)
13) MIT Technology Review: https://www.technologyreview.com/2017/08/24/149518/amazon-has-developed-an-ai-fashion-designer/ (アクセス日 2021.12.10)
14) Deloitte: Garment 2025: What new business models will emerge?, Deloitte Digital (2020) , pp.1-17.
15) Nikolina Šajn: Environmental impact of the textile and clothing industry: What consumers need to know, European Parliamentary Research Service, European Union (2019), pp.1-10.

第5章　3Dプリンティング／アディティブ・マニュファクチャリング

近年、3Dプリンタに代表されるアディティブ・マニュファクチャリング（以下、AM）技術の進展が見られる。AM技術により大量生産や大量廃棄を回避できる可能性があり、また軽量化により輸送のための燃料消費の削減も期待できことから、ライフサイクルでのエネルギー消費量の低減やCO_2排出の削減に大きな効果を有する可能性がある。本節では、主にAMのサステナビリティ（エネルギーや環境に与える影響等）に関する文献の調査について報告する。

5.1　3Dプリンティング／AMの概要

5.1.1　3Dプリンティング／AM技術

AMの特長としては、従来の金型を作っての成形や切削によるSubstractive manufacturing（除去加工、減法製造）と異なり、複雑な形状や小さな製品を製造できるという利点がある。主な材料と製法には図 5-1に示すものがある。

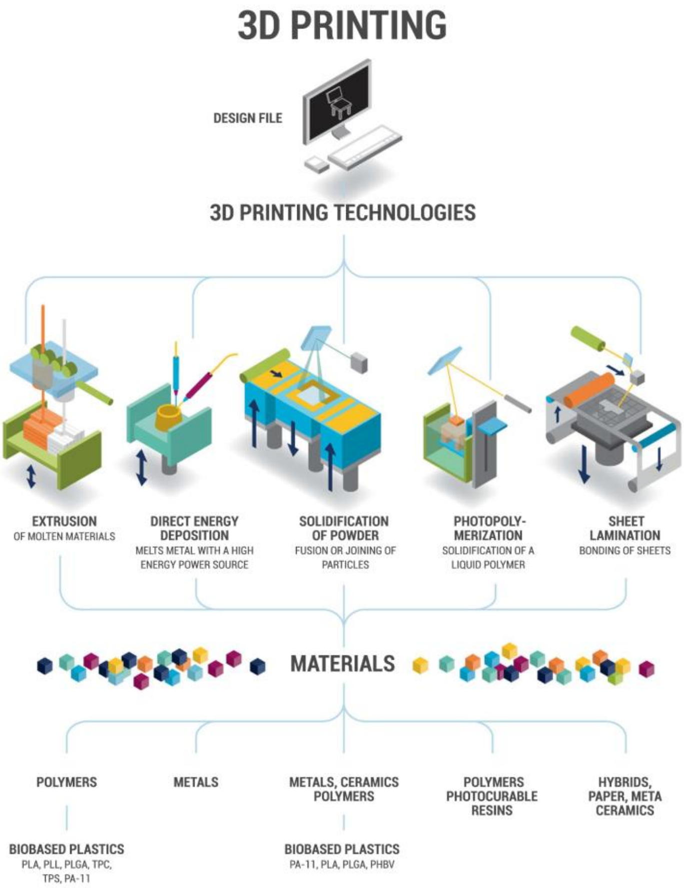


図 5-1　3Dプリンティング技術（出典：Verhoef et al.[1]）

5.1.2　3D プリンタのマーケット

L.A. Verhoef et al.[1)]によると、AM 技術は 1980 年代に高速のプロトタイプ製造として現れ注目されるようになった。2010 年代半ば頃から市場規模と応用範囲が急速に拡大し、2020 年の市場規模予測は 200 億ドル以上で、主な適用分野は消費財・電子機器、自動車、医療・歯科、産業機械等にわたる（図 5-2）。令和元年度特許出願技術動向調査[2)]によると、3D プリンタ関連の世界市場規模（3D プリンタ本体＋3D プリンタ用材料＋3D プリンタ関連サービス）は 2019 年に 138 億ドル（約 1 兆 5,180 億円）に達し、年間成長率が約 20%で、2022 年までに 230 億ドル（2 兆 5,300 億円）になると予想されている。また、AM による軽量化は輸送セクターに影響を与えることから、ITF のレポート等にも AM 技術に関する記述が見られる。ITF Transport Outlook (2019)[3)]では、世界の 3D プリンタの販売数は 2005～2011 年の間に倍増し、2017 年には 5,000 ドル以上の産業用 3D プリントシステムの販売数は前年比 80%増であったこと、また 2016 年に企業が 3D プリントや関連サービスにかけた金額は 60 億ドルにもなったことが報告されている。3D プリンティング関連コストの低下によりこの産業は急速に拡大する見込みがあり、ビジネス、家庭における今後の 3D プリンティングの幅広い展開を牽引するのは、プリンティングの質・サイズ・スピードといった技術的進歩、購入・保守・耐久性に関わるコストの低下等であるとしている。

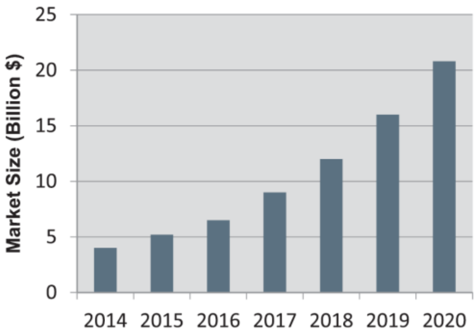


Fig. 2. Additive manufacturing market size and forecast to 2020 (Wohlers, 2014), predicting a market size of USD 20 billion by 2020.

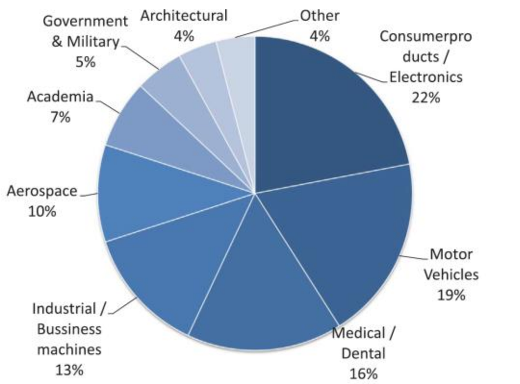


Fig. 3. Distribution of additive manufacturing revenues over business sectors showing the widespread application (Wohlers, 2014).

図 5-2　AM の市場規模（左）と適用分野（右）（出典：Verhoef et al.[1)]）

5.2　AM のエネルギー需要に与える影響に関する文献

サステナビリティの観点で 3D プリンティング／AM が注目されてきており、関連した論文や報告も多く発表されている。本節では、AM のエネルギー需要や CO_2 排出に与える影響について記述した幾つかの文献の概要を示し、特に、AM が将来のエネルギー需要に与える影響について評価した、L. A. Verhoef et al.の論文[1)]について紹介する。

5.2.1 輸送部門に与える影響

ITF[3)]は 3D プリンティングが輸送に与える影響について次のように考察している。3D プリンティングは従来の subtractive な製造方法に比べて、原料や廃棄物が削減され、また商品を最終利用に近い地点で製造できるという利点がある。異なる場所で部品を作り複雑なサプライチェーンで集める代わりに、3D プリンティングの原料を製造地点に運ぶため貨物輸送活動が低減することから、3D プリンティングが大幅に導入されれば貨物輸送が減りコスト削減となる。最近の推計によると 3D プリンティングは製造の 50%を占める可能性があり、2040 年までに世界貿易が 38%減る（最も disruptive な推計）。一方、3D プリンティングによる実質的な影響の方向性と規模については専門家間で一致していないと指摘している。例えば、OECD[4)]は、3D プリンティングが製造業やグローバルサプライチェーンに与える大きなポテンシャルを持つが、輸送や物流システムに破壊的な影響を与えると考えるのは現実的ではない、3D プリンティングが低コストで大量生産できる従来の製造方法に匹敵するほどではなく、大幅なコスト削減がなければ大量生産の規模にまで達する可能性は低いとしている。

また、ITF による推計では、3D プリンティングが CO_2 排出削減に大きな影響を与える可能性があり、2050 年までに運輸による CO_2 排出を Current ambition scenario（公約されたものを含め現行の緩和策が継続されるとするシナリオで、航空部門において現時点で disruptive なポテンシャルのある発展や技術を想定）に対し 27%減少するとしている。さらに、各種文献にある最も disruptive な 3D プリンティングの推計を想定すると、図 5-3 に示すように物流のグローバルチェーンに大規模な変化が起こり、特に東アジアにおいて貨物フローの大幅な低下が見られるとしている。

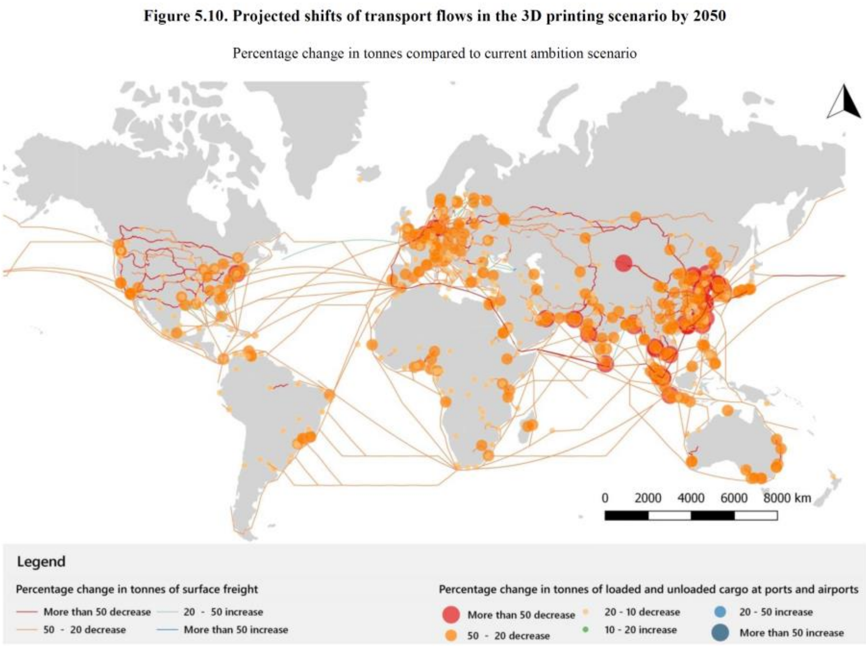


図 5-3　3Dプリンティングシナリオにおける2050年までの輸送フローの変化（出典：ITF[3]）

5.2.2　産業部門に与える影響

T. Peng et al.[5]は、産業部門が2012年の世界エネルギー消費の22%を占め、サステナビリティに向けた変革が最も必要なセクターと考えられると指摘している。AMはエネルギー・資源集約的な製造プロセスでの必要物の削減ポテンシャルを持ち、サプライチェーンにおける原料の削減やより環境に良い業務を提供し得るが、一方、どのようにそのポテンシャルのある便益を実現するかについてはあまり注目されていないとする。そして、Manufacturingにおける AMのサステナビリティに関し、図 5-4に示す3つの分野（経済、環境、社会）のうち、特に環境分野における3つの側面から考察を行っている。

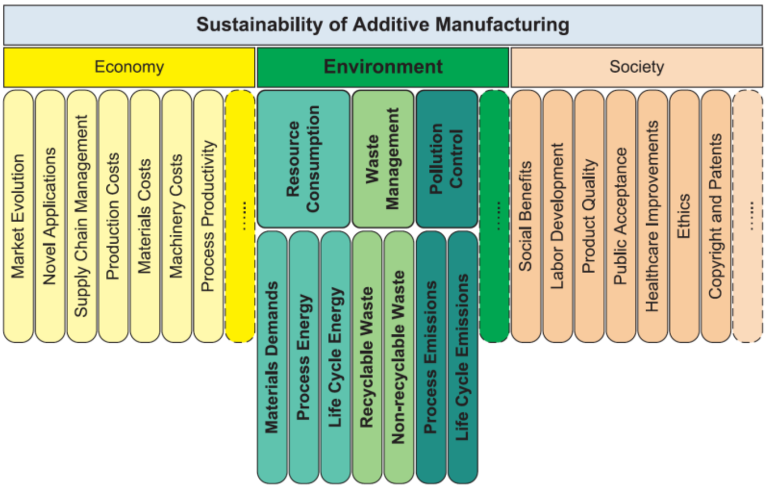


Fig. 3. Three aspects of environmental impact in the context of SAM.

図 5-4　AM の環境分野における影響の 3 つの側面（出典：Ping et al.[5]）

5.2.3　AM のエネルギー需要に与える影響に関する定量的評価

L. A. Verhoef et al.[1]は、AM が世界のエネルギー需要に与え得る影響について、2050 年の 4 つのエネルギーシナリオで評価を行っている。

(1) 分析の概要

まず、2050 年の世界の社会政治状況を示す Shell Energy Scenario for 2050 の Blueprints シナリオと Scramble シナリオ、および AM の普及と効果が高い(high)場合と低い(low)場合を組み合わせた、下記 4 つのシナリオを想定する。

- シナリオ SH：グローバル化とイノベーション促進が乏しい、AM インパクト大
- シナリオ BH：グローバル化進展・イノベーション促進、AM インパクト大
- シナリオ SL：グローバル化とイノベーション促進が乏しい、AM インパクト小
- シナリオ BL：グローバル化進展・イノベーション促進、AM インパクト小

そして、航空宇宙セクターと建設セクターについて、2050 年のエネルギー消費量(AM 無し、ベースケース）を予測し、バリューチェーンの各フェーズ（原料、輸送、加工、使用、メンテナンス等）における 2050 年の想定に基づき、AM がエネルギー消費に与える影響（エネルギー削減量）を算出する。さらに、2 つのセクターの分析結果から、特定のフェーズのエネルギー削減率を使用して他セクターにおけるエネルギー削減率を計算し、世界全体の削減量（率）の集計を行う。

(2) 分析の結果（航空宇宙セクター、建設セクター）

① 航空宇宙セクター

航空宇宙セクターの 2050 年エネルギー消費予測（AM 無しの場合）は、Scramble シナリオでは 35.4EJ/yr、Blueprints シナリオでは 20.1EJ/yr となる。ベースケースのエネルギー削減量（表 5-1）および各フェーズでの AM の普及と効果の程度（表 5-2）を考慮して、エネルギー削減量を算出し、宇宙航空セクターでは 5-25%のエネルギー低減の可能性がある。

表 5-1 航空宇宙セクターのバリューチェーンにおける削減エネルギー（出典：Verhoef et al.[1]）

Table 6
Energy savings (EJ/yr) in value chain steps for the aerospace sector, calculated using the maximum savings and the penetration percentages for each scenario in Table 4.

	Feedstock	Transport	Processing	Use	Maintenance	Total
Scramble						
Maximum savings by AM	*0.132*	*0.00122*	*0.487*	*7.37*	*0.746*	*8.74*
Energy savings SL	0.026	0.00049	0.097	1.47	0.299	1.90
Energy savings SH	0.099	0.00122	0.292	5.90	0.746	7.03
Blueprints						
Maximum savings by AM	*0.075*	*0.00069*	*0.276*	*4.18*	*0.424*	*4.96*
Energy savings BL	0.030	0.00014	0.111	1.67	0.085	1.90
Energy savings BH	0.075	0.00069	0.276	4.18	0.424	4.96

表 5-2 航空宇宙セクターにおける AM の効果と普及の程度（出典：Verhoef et al.[1]）

Table 5
Effect and penetration percentages of additive manufacturing in value chain steps of the aerospace sector. The SL and BL scenarios have the lowest penetration percentages (20–40%). The SH scenario has higher penetration percentages (60–100%). For scenario BH, full penetration (100%) over all steps in the chain is assumed.

Scenario	Feedstock	Transport	Processing	Use	Maintenance
SL (Scramble – low AM)	20%	40%	20%	20%	40%
SH (Scramble – high AM)	75%	100%	60%	80%	100%
BL (Blueprint – low AM)	40%	20%	40%	40%	20%
BH (Blueprint – high AM)	100%	100%	100%	100%	100%

② 建設セクター

建設セクターが世界のエネルギー消費の 31%を占める（GEA）ことから、同セクターの 2050 年エネルギー消費予測（AM 無しの場合）は、Scramble シナリオでは 173EJ/yr (557EJ/yr×31%)、Blueprints シナリオでは 159EJ/yr (513EJ/yr×31%)となる。ベースケー

スのエネルギー削減量（表 5-3）および各フェーズでの AM の普及と効果の程度（表 5-4）を考慮して、建設セクターでは 4-21%のエネルギー低減の可能性がある。

表 5-3　建設セクターのバリューチェーンにおける削減エネルギー（出典：Verhoef et al.[1]）

Table 9
Energy savings (EJ/yr) in value chain steps for construction sector, calculated using the maximum savings and the penetration percentages for each scenario in Table 6.

	Feedstock	Transport	Construction	Use	Other	Total
Scramble						
Maximum savings by AM	*8.63*	*3.45*	*0.00*	*23.8*	*0.00*	*35.8*
Energy savings scenario SL	1.73	0.69	0.00	4.75	0.00	7.2
Energy savings scenario SH	6.91	2.76	0.00	19.0	0.00	28.7
Blueprints						
Maximum savings by AM	*7.95*	*3.18*	*0.00*	*21.9*	*0.00*	*33.0*
Energy savings scenario BL	2.39	0.95	0.00	8.75	0.00	12.1
Energy savings scenario BH	7.95	3.18	0.00	21.9	0.00	33.0

表 5-4　建設セクターにおける AM の効果と普及の程度（出典：Verhoef et al.[1]）

Table 8
Effect and penetration of additive manufacturing in value chain steps of the construction sector. All scenarios have a 100% penetration in the construction step. In the other steps, the SL scenario has the lowest penetration percentages (20–50%). The BL scenario has a somewhat higher penetration (30–40%), except for ‘other’, which is set at 100%. The SH scenario has higher penetration percentages (50–100%). For scenario BH, full penetration (100%) over all steps in the chain is assumed.

Scenario	**Raw materials**	**Transport**	**Construction**	**Use**	**Other**
SL (Scramble – low AM)	20%	20%	100%	20%	50%
SH (Scramble – high AM)	80%	80%	100%	80%	50%
BL (Blueprint – low AM)	30%	30%	100%	40%	100%
BH (Blueprint – high AM)	100%	100%	100%	100%	100%

(3) 分析の結果（世界エネルギー需要の推計）

2 つのセクターの分析結果から、特定のフェーズのエネルギー削減率を使用して、表 5-5 に示すように他セクターにおけるエネルギー削減率を計算する。世界エネルギー需要について、各シナリオにおける 2050 年世界一次エネルギー消費（表 5-6）とエネルギー削減率を用いて経済セクター毎に推計し、世界全体の削減量（率）を集計する。こ

れらの結果に基づき、2050 年の世界エネルギー需要の 26-138EJ/yr（5-27%）の低減が可能である（図 5-5）。

表 5-5　他セクターへの適用の推計で使用されたフェーズとエネルギー削減率（出典：Verhoef et al.[1)]）

Table 11
Energy demand reduction for all economic sectors in each of the four scenarios, and the value chain steps results which were used from the two cases (Construction and Aerospace).

Sector	Value chain steps results from cases used for calculation	SH	BH	SL	BL
Transport	Average of 'Transport' and 'Use' in aerospace case and 'Transport 'in the construction case	34%	38%	11%	11%
Residential	'Use' step in construction sector	9%	14%	2%	6%
Agriculture & other industries	Average of 'Processing' from aerospace case and 'Construction' from construction case	11%	18%	4%	7%
Heavy industry	Average of 'Raw materials' from aerospace sector and 'Raw materials' from construction sector	51%	67%	13%	25%
Services	AM is assumed to have no effect on services	0%	0%	0%	0%
Non-energy use	Zero	0%	0%	0%	0%

表 5-6　各経済セクターにおける 2050 年世界一次エネルギー消費（出典：Verhoef et al.[1)]）

Table 2
Global primary energy use in 2050 for six economic sectors, in *Scramble* and *Blueprints* scenarios (Shell, 2008b).

Economic sector	Global primary energy use (EJ/yr)	
	Scramble	Blueprints
Transport	176	140
Residential	122	117
Agriculture & other industries	85	84
Heavy industry	80	79
Services	40	39
Non-energy use	54	55
TOTAL	**557**	**513**

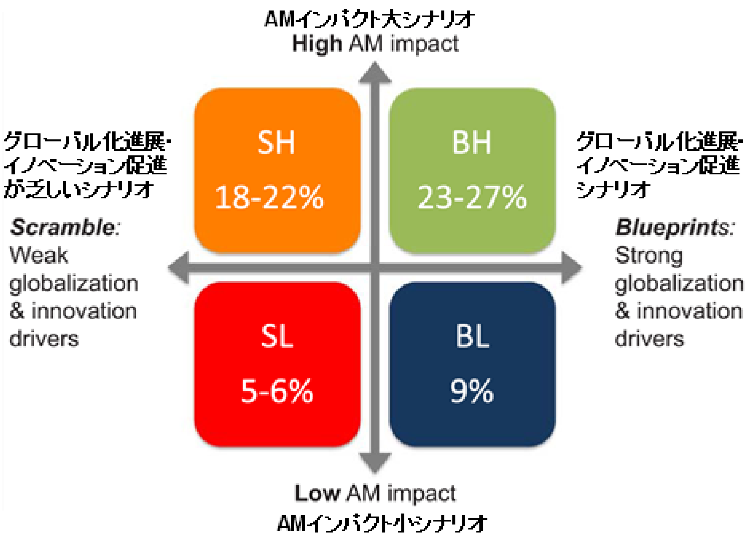


図 5-5　AM による世界のエネルギー需要削減ポテンシャル（出典：Verhoef et al.[1]に基づき作成）

5.3　まとめと今後の定量的な分析の展望

本章では、ライフサイクルでのエネルギー消費量低減、CO_2 排出削減に大きな効果を有する可能性のある 3D プリンティング／AM を取り上げ、その世界エネルギー需要に対する効果について、2050 年に向けボトムアップ的に定量的な分析を行った論文を紹介した。

ここで取り上げた論文の分析では、3D プリンティング／AM 技術によって、相当大きな省エネ効果を推計している。ただし、輸送部門での評価は相対的には精緻な分析を行っているものの、その他の部門については粗い分析に留まっており、過大な省エネ効果の推計となっている可能性もある。3D プリンティング／AM 技術の今後の進展を注視すると共に、3D プリンティング／AM がエネルギー需要サイドに与える影響について、より詳細な想定と分析の検討が必要であるが、DNE21+モデルの分析にどのような前処理をして落とし込み、より精緻な全体システムでの分析・評価を行えるかは、今後、検討が必要な課題である。

参考文献（第 5 章に関するもの）

1) L. A. Verhoef et al., The effect of additive manufacturing on global energy demand: An assessment using a bottom-up approach, Energy Policy, 112, pp.349-360 (2018)
2) 経済産業省、令和元年度 特許出願技術動向調査 結果概要 3D プリンタ https://www.meti.go.jp/press/2020/04/20200430003/20200430003.html
3) ITF, Transport Outlook 2019
4) OECD, The Next Production Revolution: Implications for Governments and Business; Chapter 5 - 3D printing and its environmental implications (2017)

5) T. Ping et al., Sustainability of additive manufacturing: An overview on its energy demand and environmental impact, Additive Manufacturing, 21, pp.694-704 (2018)

第6章　まとめと今後の課題

本調査研究では、エネルギー需要側対策の可能性に関する調査・分析・評価を行った。本報告書では、そのうち、デジタル化に伴うエネルギー需要、CO_2 排出への影響として、完全自動運転車を取り上げ、それがカーシェア・ライドシェア普及に及ぼす影響と、更にその波及効果について世界温暖化対策評価モデル DNE21+を用いて実施した結果を第 2 章に記した。第 3 章では、需要予測等の情報技術の活用により、世界の食品ロスが低減された場合の、生産・サービス、エネルギー消費、CO_2 排出への影響を産業連関表に基づき分析した内容を記した。第 4 章では、アパレル関連のライフサイクルでのエネルギー消費、CO_2 排出の評価例を調査すると共に、排出削減に向け、サーキュラー・ファッション、実店舗を必要としないオンライン販売等の取り組みの動向について整理した。第 5 章では、ライフサイクルでのエネルギー消費量低減、CO_2 排出削減に大きな効果を有する可能性のある 3D プリンティング／AM を取り上げ、その世界エネルギー需要に対する効果について、2050 年に向けボトムアップ的に定量的な分析を行った論文を紹介するとともに、課題を整理した。

以上により、デジタル化とそれに関連する技術の進展によって誘発される産業構造や生活スタイルの変化が、低エネルギー需要・低 CO_2 排出に寄与する可能性が示唆された。一方、そのような技術の実現可能性、実社会における普及の障壁、さらにリバウンド効果等、これまで必ずしも十分に考慮できていない点ついては留意が必要であり、これらも踏まえて需要側対策のモデル化・分析を拡張していくことが今後の課題として挙げられる。その上で、エネルギー供給側対策と一体的に、システム分析・評価をすることが重要と考えられる。

Empirical analysis of the impact of the Covid pandemic on electricity demand

Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC),
RFF-CMCC European Institute on Economics and the Environment (EIEE)

February 2022

Abstract

This report evaluates the impact on electricity demand of the restrictions in mobility that followed the Covid-19 pandemic. It empirically investigates how power systems in five European countries have dealt with this unexpected shock due to the Covid-19 lockdowns, that drastically changed electricity load, the scheduling of dispatchable generation technologies, electricity day-ahead wholesale prices, and balancing costs. Moreover, we complement this analysis using granular data coming from high-frequency smart-meters in Italy, to empirically analyse patterns in residential consumption during the lockdown.

1 Introduction

Despite the increase in the residential electricity demand of nearly the entire world population spending more time at home, lockdown measures to cope with the Covid-19 pandemic have resulted in an unprecedented drop in total electricity demand (Buechler et al., 2020; Prol and Sungmin, 2020). Across European countries, electricity demand during the 1st lockdown phase has fallen on average by 10%–15% (Chen et al., 2020; Cicala, 2020; McWilliams and Zachmann, 2020; Narajewski and Ziel, 2020).

The shock induced by the governments' response to the pandemic has occurred during the structural transformation of national power systems. Since the 2008–2009 global financial crisis, variable renewable energy source (RES) capacities have been picking up, and today more than 50% of the newly installed capacity for electricity generation consists of RES (Figueres et al., 2018). Newly installed RES capacity grew more than 200 GW in 2019, its largest increase ever (Murdock et al., 2020).

All regions implementing lockdown measures have undergone a noticeable shift towards low-carbon sources, with RES gaining a higher share following the sudden fall in electricity demand. These sources have near-zero marginal costs and, in Europe, are legally prioritized over fossil fuels thanks to priority dispatch connection terms.

Even if the sudden decarbonization and the resulting reduction in carbon emissions from power generation experienced during the Covid-19 lockdowns is a temporary phenomenon induced by the unprecedented fall in the net-load, insights can be drawn from understanding how power systems have reacted under a generation mix composed predominantly by RES. Understanding the characteristics of power systems in which RES could easily account for 100% of the power demand in a given hour of the day may bring to the surface possible limitations of the current power systems, leading to volatility in power prices and possibly to higher costs for managing the grid. Furthermore, the high overcapacity experienced during the lockdowns can provide insight into the risks of business case deterioration of specific types of generation (fossil-based, dispatchable) and inform future systems' characteristics regarding flexible backup capacity mechanisms (Caldecott and McDaniels, 2014).

The objective of the report is two-fold. First, it aims to advance the understanding of how different features of the power systems have shaped their reaction and performance during the Covid-19 lockdowns, as well as before and after the relaxation of the containment measures. We use the power sector hourly data from January 2017 to July 2020, taken from the European Network of TSOs for electricity and build empirically grounded counterfactual scenarios. We consider five big European economies: France, Germany, Italy, Spain, and the UK, which have been heavily affected by the ongoing pandemic and account for two-thirds of installed renewable power capacity in the EU28. In particular, we develop a suite of econometric models to represent different aspects of the power systems, exploiting the real data offered by the natural experiment of very high RES penetration collected by Transmission System Operators (TSOs) during the Covid-19 1st lockdown phase. Then, we use such models to reproduce power systems' characteristics in a business-as-usual scenario (counterfactual) during the 1st and 2nd quarters of 2020. By computing the difference between the observed and counterfactual values we were able to identify the causal effect of the lockdowns. We separately consider the period preceding the lockdowns and the periods during, and following, the lockdowns.

The second objective is to evaluate the impact of Covid-19 on household residential consumption in Italy. We use hourly smart meter data recording from thousands of households from the area around the city of Bologna in Italy. Recordings are available for the years 2019 and 2020, although the households for the two years are not the same and for 2019 we have a lower number of users. We use a clustering approach to find groups of users that behave similarly, thus unraveling the difference in hourly and daily consumption before, during and after the first national Italian lockdown.

By combining the two sets of analyses, we can assess if the daily dynamic of the transmission load during the lockdown can also be explained by the specific behavior of one of the sectors driving electricity demand, namely the residential sector.

2 Empirical Analyses

We focus our attention on how the combination of demand shocks and high RES generation reduced net-load demand and thus impacted the generation schedule of dispatchable generation technologies. Covid-19 lockdowns' influence on power markets' equilibrium results from the interaction between demand and the supply side, which is determined by the sequence in which power plants with different marginal costs contribute to the generation (the merit order). When the demand curve shifted downwards during the lockdowns, the intersection between demand and supply shifted too, pushing power plants operating at a marginal cost above the new equilibrium price out of the market. This analysis allows us to investigate both the impact on hourly operations of power generators and the overall variation in the carbon intensity of the dispatchable generation mix.

We also investigate how electricity price fluctuations have reflected variations in the market equilibrium during Covid-19. Conventional generation technologies in Europe play a dominant role in setting wholesale prices as they meet the net-load, i.e. residual demand not satisfied by renewable sources (Weber, 2006). The lockdowns have remarkably reduced average wholesale electricity prices by as much as 45% in Italy, while the pan-EU average of day-ahead baseload prices reached a low of 24 euros MWh^{-1} in the 2nd quarter of 2020, down 44% year-on-year. The reasons behind this fall are to be found in the contemporaneous occurrence of low fossil fuel and carbon allowance prices during the lockdowns, as well as from the lockdown-induced demand fall. We quantify the impact of Covid-19 induced shocks on the day-ahead electricity markets by tracing the evolution of hourly wholesale electricity prices. We decompose the impact of Covid-19 on wholesale day-ahead prices between the shocks on (a) demand and (b) fossil generations' operation costs.

We also turn our attention to the balancing markets managed by TSOs. The fall in demand and the resulting change in the generation mix affected the task of balancing the electricity systems. In Italy, for instance, the weeks of lockdowns were associated with an increase in the costs incurred for ancillary operations (Graf et al., 2020). During Covid-19 lockdowns, exceptional conditions were registered to accommodate the larger-than-usual demand forecast errors, that is the deviation between the day-ahead forecast and the actual demand. Both sources of uncertainty might have required more upward and downward flexibility. In particular, the occurrence of high demand forecast errors can be considered an interesting experiment comparable to a situation where shocks of similar magnitude would occur due to very high RES penetration, as both increase the size of the net-load forecast errors. In other words, we investigate whether TSOs are able to deal with an intensification of the existing demand/supply shocks when net-load becomes more difficult to predict and the errors become larger, both in absolute terms and in relative terms compared to the total net-load (i.e. experiencing more volatility due to the stochastic unpredictability of RES and demand). A comparison across countries is particularly informative as differences in the baseload mix may result in different levels of systems' incompressibility (i.e. lack of downward flexibility), due to the different start-up and ramping costs (Brijs et al., 2015).

Containment measures have taken different degrees of stringency across Europe, sometimes with regional differentiation. For cross-country comparability, we classify the nation-wide measures used at the time of writing in five categories ('school closure', 'domestic curfew', 'commerce halt', 'commerce halt—partial', 'non-essential activities halt').

We estimate different counterfactual scenarios in which the Covid-19 induced shock does not occur for the: (a) electricity load and renewable generation's share in the power mix (b) the capacity factor of dispatchable technologies, their share in the dispatchable generation mix and the resulting carbon intensity of the dispatchable generation mix; (c) wholesale day-ahead prices (d) balancing markets' costs. Details on the methodology adopted for the power sector analyses can be retrieved in Colelli et al. (2021).

As for the analyses on residential electricity consumption, using hourly smart metering data, we employ machine learning techniques, and in particular clustering, to better understand patterns of consumption. We identify groups of users that behave similarly, thus unraveling the difference in hourly and daily consumption before, during and after the first national Italian lockdown. In particular, the analysis aims to evaluate the impact of lockdowns on the average daily consumption of domestic users. Since electricity consumption changes depending on seasonality, day of the week, and special holiday (i.e. Easter), it is crucial to make a comparison between the consumption in 2020 and the trend in the previous year.

We select the period between the first of February and the end of May, for both 2019 and 2020. For each household, we use the time-series of the (z-standardize) average (of the log of) daily consumption. In order words, we get a signal with the average electricity consumption for each day in the four months. For 2019, between the first of February and the end of May, we have 119 valid days; the users are 163. For 2020, in the same period we have 120 valid days, and 518 households. We select only households in city of Bologna.

We divide the period February-May 2020 in four-time intervals, and we projects the same intervals on 2019 for comparison: a) before Covid-19 (from the first of February to the 9 of March; b) first part of lockdown (until 29 of March; c) second part of lockdown (until the 4 of May, when reopening of activities started in 2020); d) after (until the end of May).

For the identification of consumption patterns, we cluster the signals, using k-means algorithm, and the elbow method to determine the number of clusters. Throughout the analysis, we consider two-time scales of signals to cluster: the daily consumption for the whole period February-May (2019 and 2020), and the hourly consumption for a day - selected for the same period. While the whole-period-clusters shed light into the overall variation in consumption throughout the pandemic phases, the day clusters are helpful to unravel the daily habits of people. Section 2.5 presents the results.

2.1 Increase in RES penetration due to the fall in power load

This section presents the findings on how the power systems in five European countries have dealt with this unexpected shock due to the Covid-19 restrictions. Results indicate that the power system had rapidly responded to the lockdowns, when electricity demand was plummeting with the intensification of restrictions' stringency across all countries. Compared to the counterfactual demand that would have occurred in the absence of the Covid-19 lockdowns, the drop in average daily transmission load has increased with the intensification of restrictions across all countries, especially in Italy and Spain (Figure 1, panel (a)). The 'commerce halt' and 'commerce halt-partial' policies reduced electricity load on average by 10%–15% across the five European countries analyzed. Further stopping all non-essential production activities, resulted in an average reduction of 25% in Italy (surpassing 30% at the onset) and of 22% in Spain (Figure 1, panel (b)). Inspection of the hourly load profile (Figure 1, panel (c)) reveals that all countries experienced a fall in demand from 5 am to 10 pm, with the highest negative spikes around the morning (7–8 am) and evening (6–7 pm) peaks. Higher-than usual domestic activities between 12am and 3pm have compensated the industrial and commercial drops to some extent, leading to smaller reductions. This effect is particularly strong in France, Spain and Italy, suggesting that sectoral responses have differed across countries, possibly depending on different production and consumption behaviors. The analysis of the electricity demand by households presented in Section 2.5 below will confirm this interpretation.

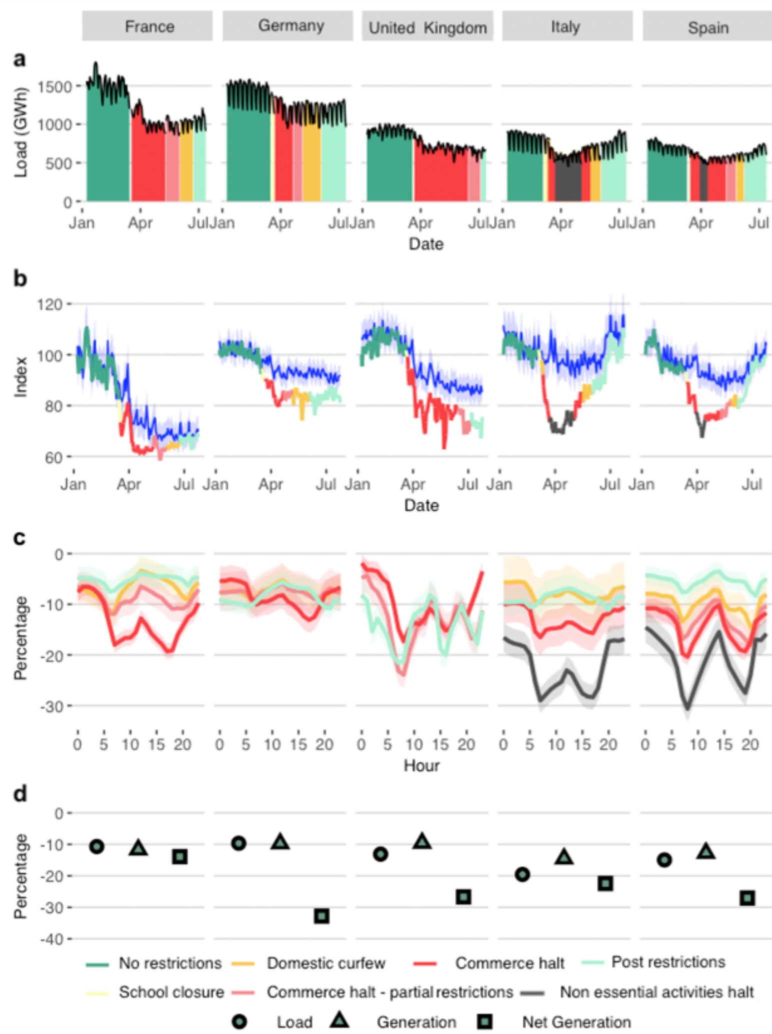


Figure 1: COVID-19 lockdowns' shocks on electricity demand and generation.

Notes: Panel a: Electricity load during the COVID-19 period: Daily total electricity transmission load during the COVID-19 period. Panel b: Counterfactual and observed daily load, indexed against the Jan 1st observed daily load. The dark (light) blue lines represent the estimate counterfactual load (95% confidence interval). Colored lines represent the observed daily load during both pre-policy and policy periods. Panel c: Mean hourly variation between observed and counterfactual load during the policies. Lines (shades) represent the mean hourly variation (95% confidence interval) of power load, induced by the lockdown policy. Panel d: Cumulative reduction of the load, generation and net generation from the counterfactual level during the implementation of lockdowns. The "School closure" measure is excluded from Panel c and Panel d as during the few days of its implementation, the policy led to relatively small and non-statistically significant variations in demand, ranging from -3% to +6%.

The fall in the power load has resulted in an upward shift of RES penetration rates in all countries, although the magnitude varies depending on the power system (Figure 2). On average, RES has contributed up to 60% of the total active generation in Germany (an additional 15% point increase compared to the counterfactual mean shares), around 50% in Italy and Spain (an additional 5%–10% point increase), up to 40% (an 8% point increase) in the United Kingdom and up to 20% in France (3%–5% point increase). A clearer picture of the remarkable increase in RES penetration can be assessed by inspecting the maximum share of RES generation observed during the lockdown phases: RES contributed a maximum of 76% of total active generation in Germany, 60%–70% in Spain, Italy and the United Kingdom and 40% in France.

Lockdowns have shifted the average contribution of solar energy up by 8%–15% points across all countries except in France (where they were up only by 2%–3% points), during the central hours of the day. As a result, the average hourly share in the mix has ranged from 20% in Spain to 40% in Germany. The impact on wind generation resulted in a smaller absolute change (except for Germany), as wind contributed relatively little or during the hours in which net-load dropped less (night-time). The share of non-dispatchable hydropower has increased by roughly 5% points during evening peaks and night hours in all countries except the UK, where the technology's contribution to the mix is limited. The 1st direct impact of RES contributing up to 60%–70% in power generation due to the COVID-19 demand shocks can be assessed by looking at power generation's market equilibrium, resulting in a reduction of the dispatching of power plants operating at the margin, sharp modulations of the generation mix, and downward pressure on wholesale prices.

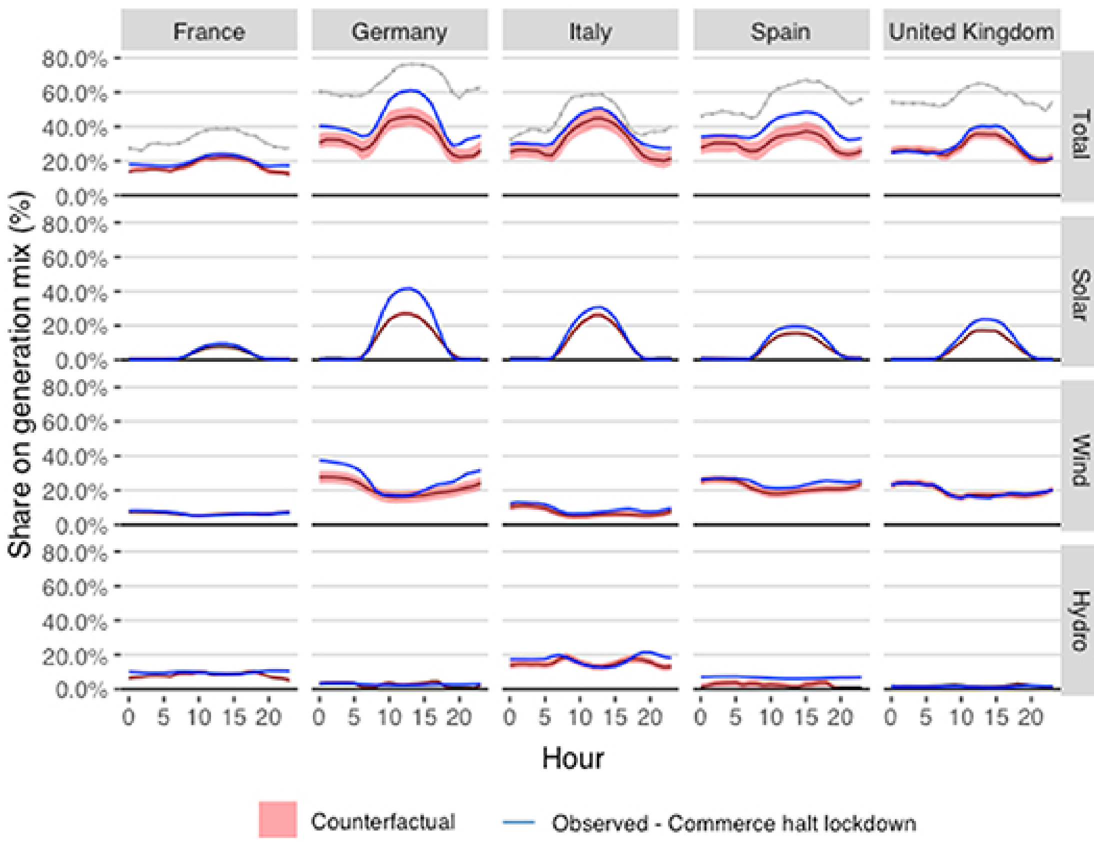


Figure 2: Covid-19 lockdowns' shocks on the share of hourly RES generation

Notes: The figure reports the observed (blue line) and counterfactual (red line and red shaded area) shares in the electricity systems of total RES, solar, wind and non-dispatchable (i.e. river-based) hydropower. The estimated counterfactual and 95% confidence interval are computed based on the econometric estimation of the policy-induced shocks. Grey lines report the maximum observed share occurred during the policy period. Only the 'commerce halt' policy phase is shown.

2.2 Changes in the profile of dispatchable generation

We now compare the counterfactual capacity factor with the observed hourly mean values during the lockdown phase across countries (we focus our results on the two most stringent lockdowns, the 'commerce halt' lockdown phase in Figure 3). The difference between the observed and counterfactual mean hourly capacity factor of the technologies corresponds to the estimated impact of the net-load shock on the contribution of each technology to the power system in each country. A smaller total capacity factor means that a smaller share of the technology's total available capacity contributed to the power system compared to the counterfactual scenario. The change in the curvature of the line through the hour of the day signals that the technology is ramped up/down for flexibility purposes and is mainly used to accommodate peak loads. The variation of the estimated impact on the capacity factor throughout the day indicates the extent to which the net-load shock influenced the ramping requirements of each technology. This can signal the extent to which technologies could adjust to the circumstances and contribute to the power system alongside a relatively high share of RES to fulfill load requirements. Such a time-varying capacity factor characterizes all technologies except for nuclear-based generation, which exhibits a uniform shape through the hours.

Policy-induced net-load shocks have resulted in a fall in the utilization of fossil fuels, ranking higher in the merit-order curve compared to hydro and nuclear. Accordingly, the carbon intensity of the dispatchable generation mix has fallen sharply during the lockdowns, resulting in a large reduction of emissions (see supplementary methods). We compute the COVID-19 induced marginal reduction in the dispatching of each conventional technology and apply country-specific coefficients of the emissions related to their operations (based on Tranberg et al. (2019)): we find that the net-load shocks have contributed to reduce emissions not only by the average emission factor per kilowatt-hour, but by a higher amount because generation from the more carbon-intense technologies has been cut compared to counterfactual conditions. Across the five countries, total power emissions decreased by about 26 $MtCO_{2eq}$. Emission savings have originated both from energy demand reductions (17 $MtCO_{2eq}$), and fuel switching (9 $MtCO_{2eq}$).

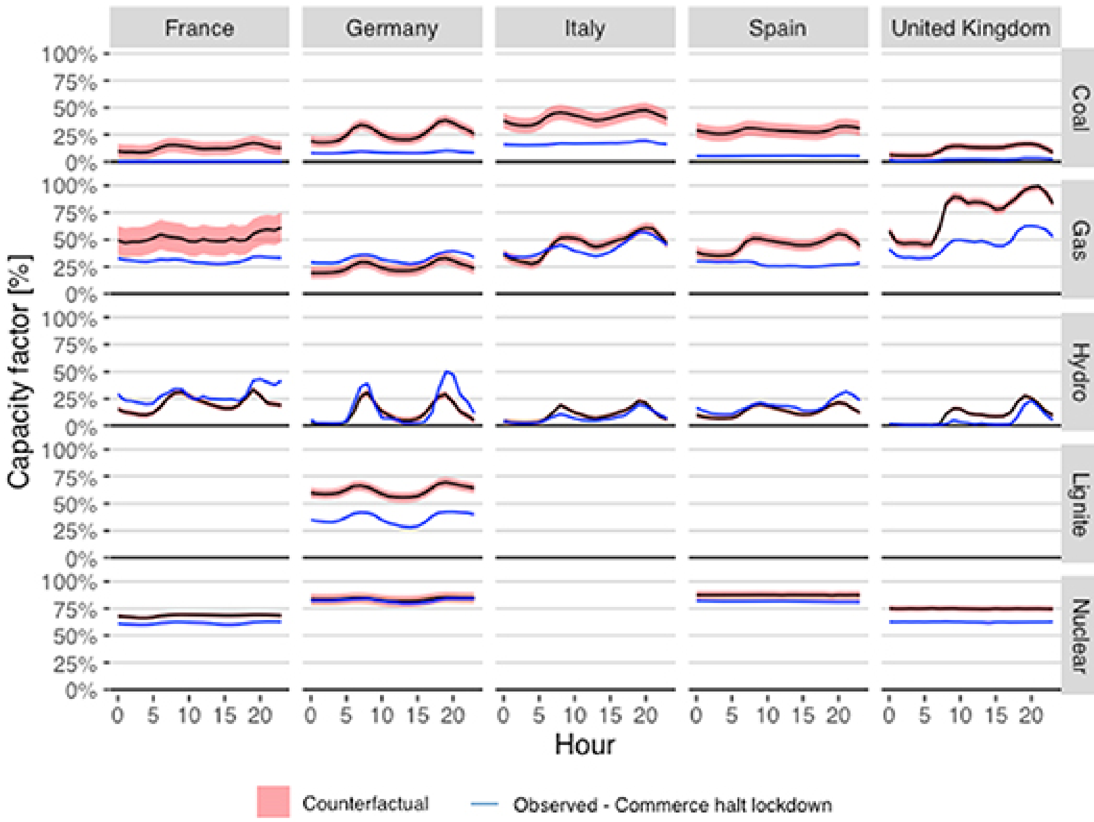


Figure 3: Covid-19 lockdowns' shocks on the hourly capacity factor of dispatchable generation, by technology

Notes: The figure reports observed (blue line) and counterfactual (red line and red shaded area) capacity factor of dispatchable generation under the 'commerce halt' policy phase.

2.3 Drivers of the shock in wholesale day-ahead prices

In this section, we present the comparison between two counterfactual scenarios of day-ahead wholesale electricity prices: (a) seasonal scenario, in which we simulate the evolution of day-ahead wholesale electricity prices based on the observed variation in renewable energy generation, the observed daily maximum temperature and the calendar effects, holding the value of the operative costs (OC_d^n) fixed to the mean level in 2019; (b) fuel price scenario, in which we replace the 2019 mean of operative costs (OC_d^n) with the daily observed operative costs during the lockdowns.

The difference between the seasonal and the fuel price counterfactual scenarios quantifies the impact of the Covid-19 induced shock on fossil fuels' and ETS costs (henceforth 'fuel price effect') on the wholesale day-ahead prices. The difference between the fuel price scenario and the observed day-ahead prices (blue line in Figure 4) quantifies the impact of the demand shock on the wholesale day-ahead prices (henceforth 'demand effect').

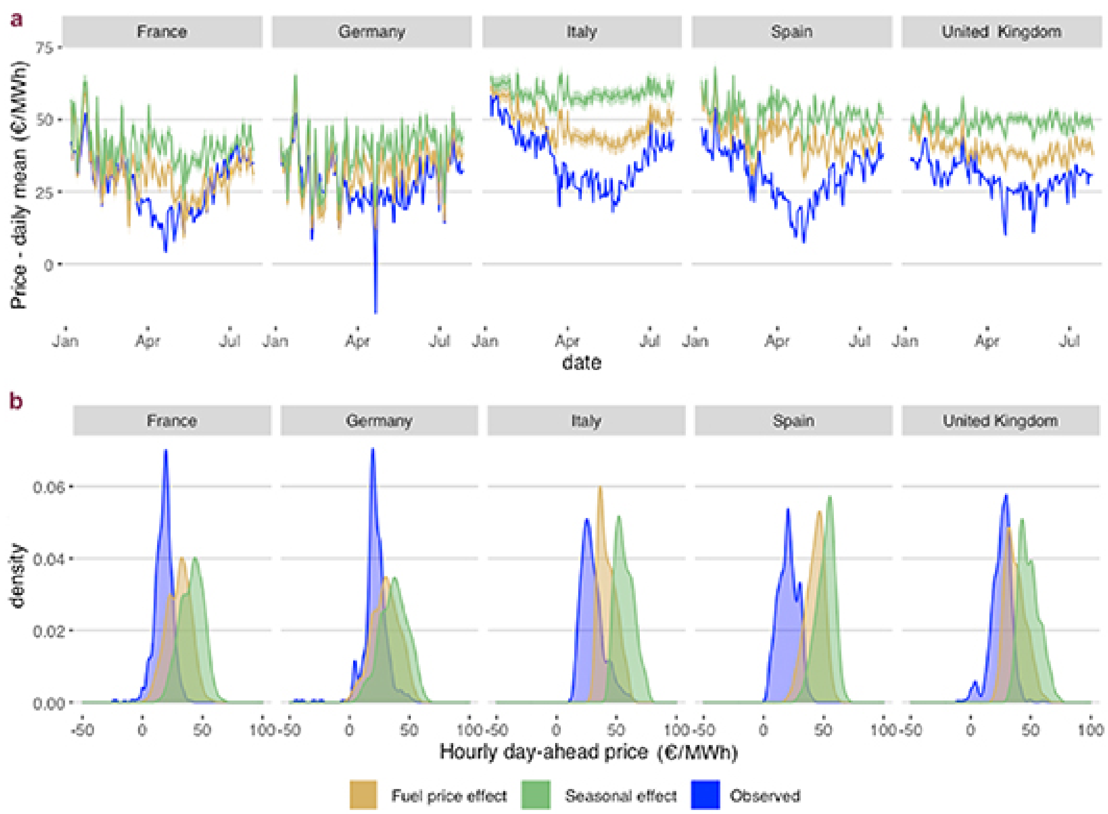


Figure 4: Daily electricity prices and distribution of observed hourly prices

Notes: Time series of observed (blue) and counterfactual (brown and green) mean daily electricity prices (panel (a)), and distribution of observed hourly prices (blue shaded areas) and counterfactual (brown and green) during the commerce halt lockdown (panel (b)).

The wholesale electricity prices fell on average between 16 and 32 € MWh^{-1} across countries, corresponding to a percentage fall ranging between 43% and 61%, due to the overall effect of the 'commerce halt' lockdown. The decomposition suggests that both the demand effect and the fuel price effect have caused a significant reduction of day-ahead wholesale prices compared to the day-ahead prices in the counterfactual scenario.

While the fuel price and demand shock contributions to the total price reduction are roughly equal in most countries, the demand effect is relatively strong in Spain and accounts for 72% of the total price fall. The relatively uniform impact of the fossil fuel effect across power systems with heterogeneous dispatchable generation mixes suggests that to provide peak load, most countries use relatively expensive gas plants. On the other hand, the relatively small role of the fossil fuel price shock in the Spanish system may be related to the role played by hydropower in the country, which reached a share of up to 35% of the dispatchable generation mix during peak hours during the lockdown (as opposed to 5%–15% in the other countries).

The distribution of the observed hourly day-ahead prices and the counterfactual hourly day-ahead prices in the counterfactual scenarios provide an indication on the tails of the distribution (Figure 4, panel (b)). Two groups of countries can be distinguished based on the variation in the density functions. In Spain, Italy and the United Kingdom the observed density functions are characterized by a leftward shift in the mean, while the overall shape of the distribution does not change considerably. The shift is stronger in Spain and Italy compared to the UK: in the former two countries the mean price observed during the lockdown (blue) falls outside the left tail of the two counterfactual prices' distributions (95th percentile of green and red distributions).

In Italy, the fall in the costs of peak-load power plants, combined with the demand shock, was sufficiently large to displace the typical import/export balance. As the gap between the (higher) day-ahead prices in the home market with respect to the (lower) day-ahead price of net exporters such as France shrunk due to COVID-19, volumes of imported power have drastically fallen with respect to the 2nd quarter of 2017–2019.

In France and Germany, the mean of the observed distribution does not shift considerably with respect to the counterfactual distributions, while the kurtosis increases considerably. The probability of observing a price of 20 € MWh^{-1}, which is the mean price during the lockdown (blue distribution), is roughly four times higher than the probability associated with the same price in the 'fuel price' counterfactual. Therefore, the demand shock has induced most of the variation in the price distribution of these countries. The similarity in the distribution of observed prices the reduction in price volatility around the mean day-ahead price in Germany and France may derive from greater market integration than the rest of the countries, as the two systems take part to the same regional wholesale market, the Central Western Europe (including France, Belgium, Luxemburg, the Netherlands, Austria and Germany), which is connected through a flow-based market coupling (Felten et al., 2019). While across Europe the day-ahead market coupling takes place ex-ante the market-clearing, in Central Western European a more flexible method has been in place since 2015 that operates simultaneously with the market-clearing (den Bergh et al., 2016).

Despite that the occurrence of high negative prices in Germany has been associated with peaks in net exports, overall the country has experienced more frequent net importing positions than during the 2nd quarters of 2017–2019. The shift towards more imports may be associated with the reduction in dispatchable power flexibility following the temporary phase out of coal generators (as underscored in Section 2.2). Similarly, the UK experienced the shift in the distribution of the hourly net import position towards larger import volumes compared to past years' 2nd quarters. This shift should be evaluated in combination with the marked reduction in gas-fired generation during the lockdown, signaling that relatively cheap power from France has been preferred for flexibility purposes to the country's gas-fired fleet.

2.4 Balancing

The fall in net-load demand and the resulting change in the generation structure not only resulted in lower wholesale prices, but also affected the task of balancing the electricity system, possibly increasing the costs incurred for grid operations. The stress on the system during COVID-19 lockdowns, characterized by the almost unprecedented condition of very low demand coupled with abundant renewable energy, results from the interaction of forecast errors for RES generation and demand.

The comparison between the observed balancing costs and the model-based projections provides contrasting evidence across the four countries analyzed: projected balancing costs during the lockdown are close to the observed balancing costs in France and the UK, while our model systematically underestimates the price spikes that characterized the German and Italian systems (Figure 5).

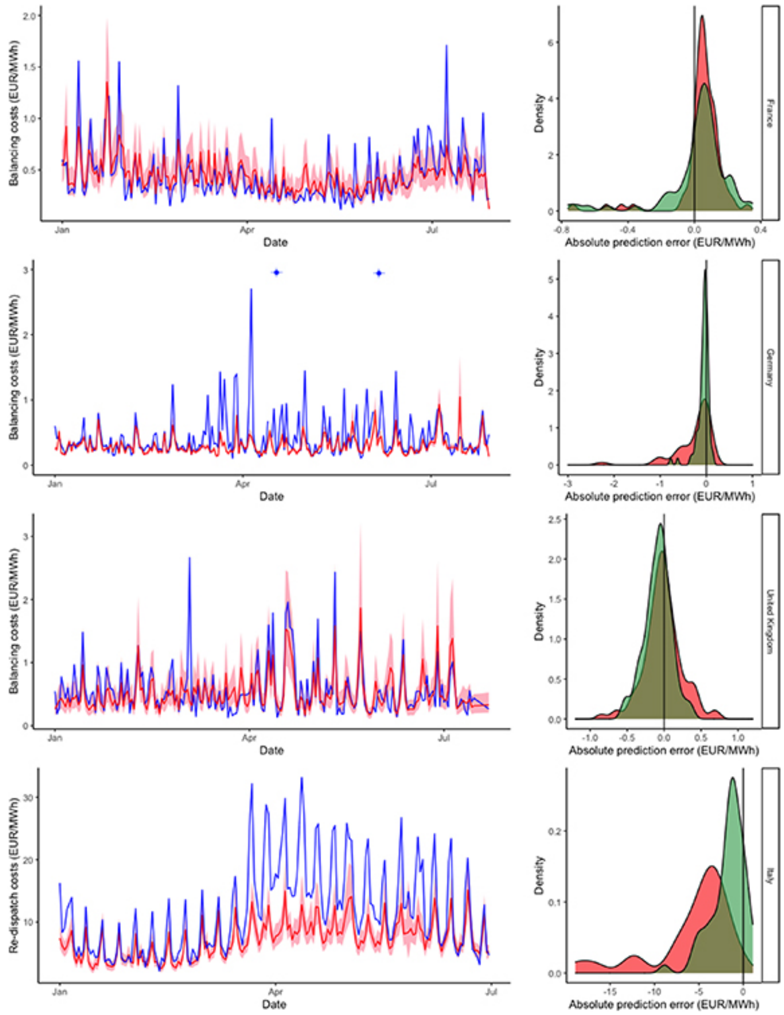


Figure 5: Daily daily balancing costs

Notes: Time series of observed (blue) and counterfactual (red) daily balancing costs from January 2020 to July 2020 (left panels). The blue markers represent outlier price conditions experienced in Germany and equal to 7.9 € MWh^{-1} (on the 6th of June 2020) and 8.4 € MWh^{-1} (on the 14th of April 2020). Distribution of forecast errors (difference between observed and counterfactual) during the 'commerce halt' lockdown (red shaded areas) and in the months preceding the lockdowns (green shaded area, right panels).

The inspection of the time series of the balancing costs per unit of demand underscores that Germany experienced very high balancing costs spikes, while Italy experienced an overall increase in the level of ancillary services' costs, which, in both cases, are not captured by the model-based projections. Germany in particular experienced two episodes when daily balancing prices were around 8 € MWh^{-1} (blue markers in Figure 5), a level which is roughly double the maximum registered in the past 3 years (equal to 4.5 € MWh^{-1}). France's balancing market has been characterized by a slight reduction in balancing costs, both as for surplus and for deficit conditions, which resulted in a slight overestimation of balancing costs by the model based on market fundamentals. The UK experienced an increase in balancing costs during the lockdowns compared to previous months, which are well described by our forecasting model based on market fundamentals.

The large abundance of gas capacity in the UK might have played a role in keeping balancing costs much more under control compared to Italy and Germany, where gas-fired capacity was either unaffected (Italy) or even decreased (Germany) due to the day-ahead power market's equilibrium shocks induced by the lockdowns.

By evaluating the difference between our out-of-sample predictions and the observed balancing costs, we shed light on the possible occurrence of new market mechanisms affecting balancing markets. The aspects which could result in a deviation of our estimates from the observed balancing costs include: (a) new offer strategies employed to exercise market power by the participants in the balancing market (for instance, the reduction in the profits of power generators resulting from low day-ahead electricity prices may have triggered an increase in the value of the bids placed by such parties in the ancillary services market); (b) a variation in the operating constraints (such as voltage regulation, reserve requirements or nodal network constraints), which can increase the requirements for re-dispatch actions (Graf et al., 2020). Overall, we find evidence for the existence of a combination of such factors from the behavior of balancing markets' costs in Germany and of ancillary services' costs in Italy.

2.5 Residential electricity pattern

This section discusses residential electricity use. Figure 6, top panel, shows the clusters of daily consumption, at the hourly resolution, obtained with k-means clustering. The daily clusters belong to the period of February-March of both 2019 and 2020, considered together. The number of clusters, six, is selected through the elbow method. The middle panel presents the distribution of daily energy consumption of the curve in each cluster. Both these plots help understand how the clusters describe the hourly behaviors of the households. The bottom panel displays the fraction of daily curves which belong to each cluster, for each of four corresponding periods in 2019 and 2020.

From the change in the frequency distribution of clusters, we see how daily consumption in Cluster (2) - small morning peak, high early evening consumption and Cluster (5) - late evening activity, decrease during lockdown. Those behaviors characterized a typical eight hours working day, outside the home. Early evening consumption in Cluster (2) remains of low prevalence also in the re-opening period, while the evening consumption for Cluster (5) regains a comparable level with the previous year. Towards the summer, daily consumption in Cluster (5) was monotonically increasing also in 2019.

The frequency of Cluster (3) - intense morning and evening consumption, does not change significantly, while Cluster (4) - uniform and low consumption, shows a slight decrease in the second part of the lockdown, probably indicating that people do not go on holiday. Finally, Clusters (1) - afternoon-evening consumption, and (6) - high afternoon-evening consumption and intense lunch-time load, as indicated in the Top Panel, increase their prevalence during lockdown, and even in the re-opening time these clusters remain more prevalent than before. In summary, daily energy load in Clusters (1) and (6) are likely to be load curves that characterize smart working.

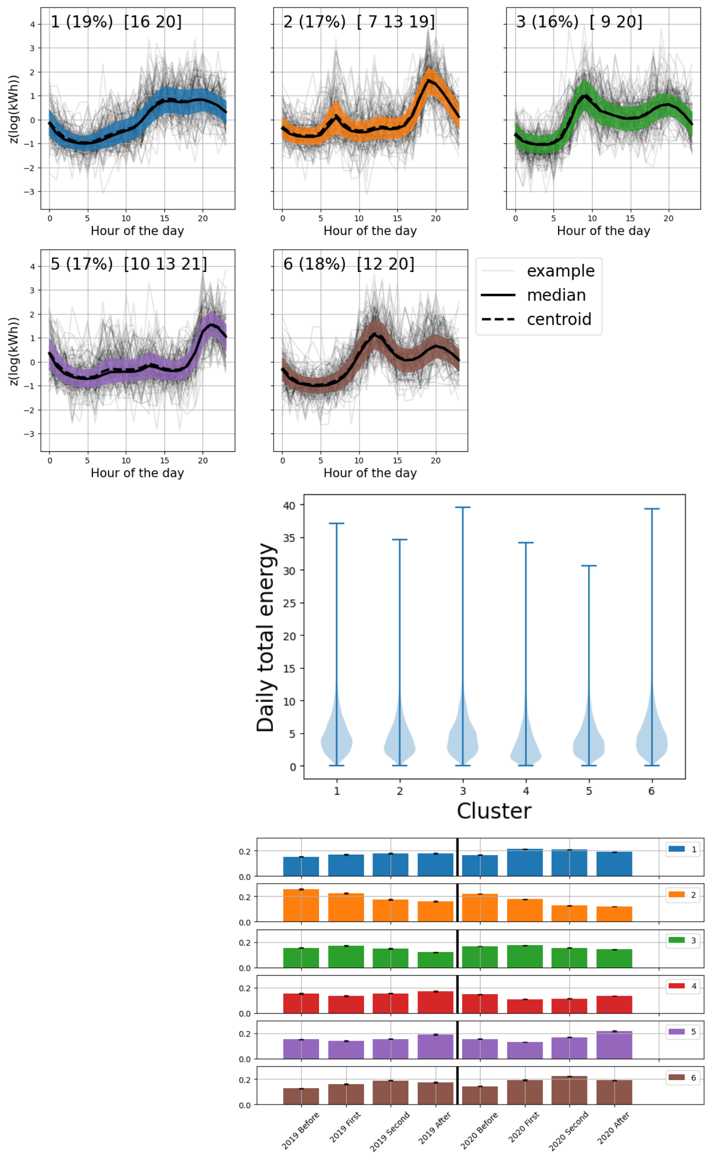


Figure 6: Hourly consumption for a day - year 2019 and 2020.

Notes: **Top Panel:** Cluster of daily consumption at hourly resolution. Data cover the period of the first COVID lockdown (from February to May) in 2020, and the same months of the previous year 2019. In the squared brackets, the timing of the peaks. **Middle Panel**: Distribution of daily total energy of the curves in each clusters. **Bottom Panel**: Frequency of daily curves belonging to each cluster, for four corresponding time periods in 2019 and 2020. The black line on top of each bar indicate the -almost invisible- standard deviation obtained with bootstrap.

With day-cluster hourly consumption analysis we show the average variation in daily behaviors. It is also interesting to characterize households depending on how the overall consumption changes with the pandemic, and eventually link these changes with possible changes in daily consumption at hourly resolution. We analyse these results for the daily consumption clusters separately for 2019 and 2020. The top panels of Figures 7 and 8, show the clusters of daily consumption obtained for 2019 and 2020, respectively.

We underline the date corresponding to daylight saving and Easter. For the 2020, the year in which lockdown and restrictions started to take place in Italy, we also underline the time interval when there was the national lockdown (09/03/2020 - 04/05/2020). The 9 of March 2020 was when the national lockdown was declared, with the closure of schools, activities and shops (a part from grocery stores, pharmacies and other essential services), and the citizens were obliged to work from home (except for *essential* workers); while on the 4 of May, many activities started to open again after the lockdown.

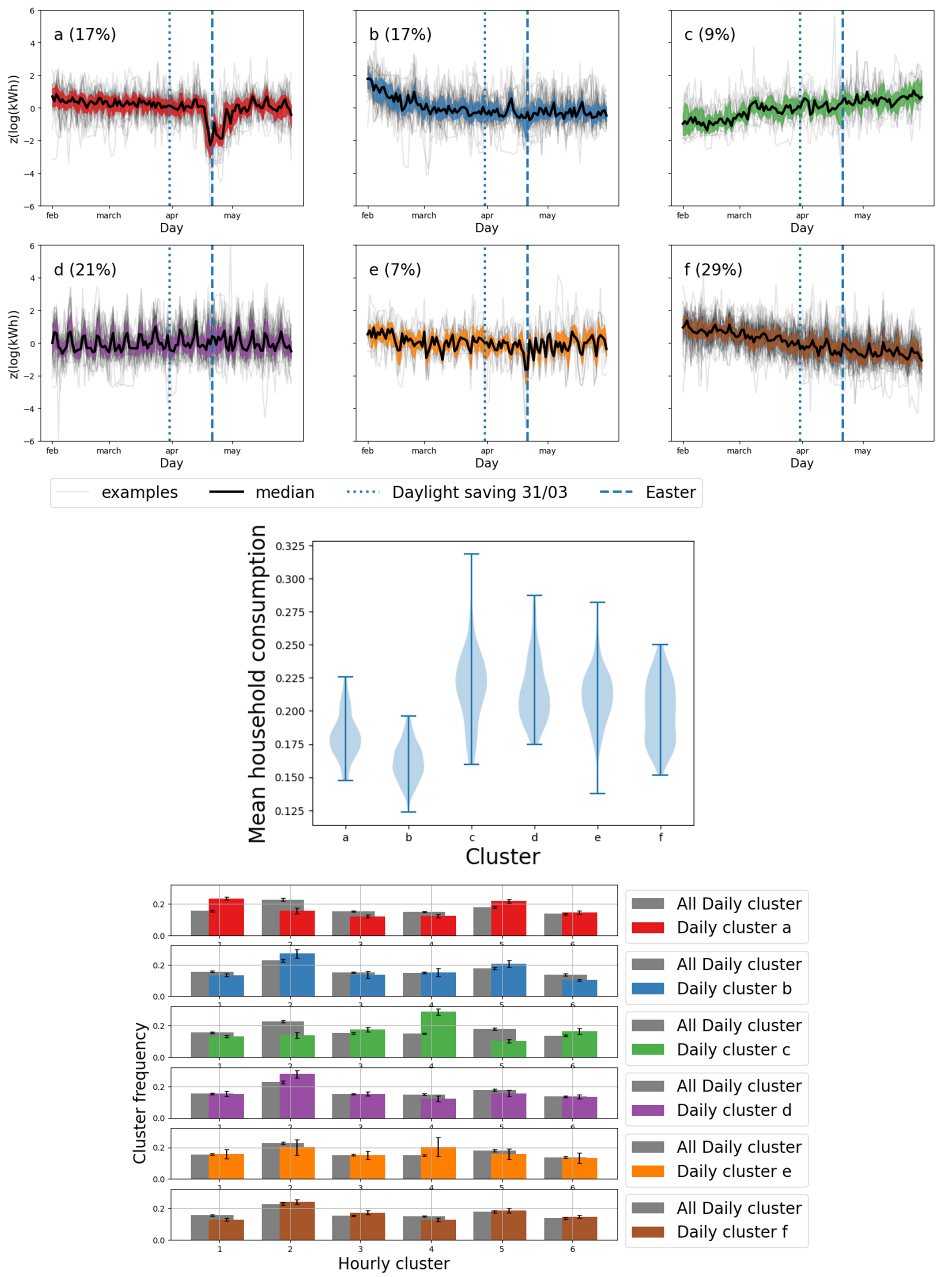


Figure 7: Daily consumption for the whole period February-May (year 2019).

Notes: **Top Panel:** Clusters obtained with k-means for the daily consumption over a period of a few months, for the year 2019. **Middle Panel**: Distribution of mean household consumption for consumers of each cluster in (a). **Bottom Panel:** For each daily cluster in (a), the distribution of hourly cluster (from Figure 6). The errors bars are the standard deviation obtained with a bootstrap procedure (10 re-sample, each with 60% of users).

In Table 1 we provide some information about household characteristics. Unfortunately, this information is available only for 2020. We show the percentage of green electricity contracts, the percentage of households where tenants are residents, and the average surface of the house in square meters.

Cluster	Green	Residents	Surface
average	37%	88%	78.39
a	33%	86%	79.27
b	27%	89%	78.73
c	43%	90%	72.76
d	30%	86%	77.70
e	33%	91%	88.48
f	38%	90%	77.27

Table 1: Percentage of household: with a *Green* contract and with *Resident* occupants; average dwelling *Surface* in square meters; these values are the average for every clusters a-f of Figure 8. The average values for all the sample are also presented.

From the cluster representation, we can see that the Easter valley of cluster (a) and (e) in 2019 is absent in all the clusters for 2020, indicating that obviously people in 2020 have not been able to go on vacation on those days.

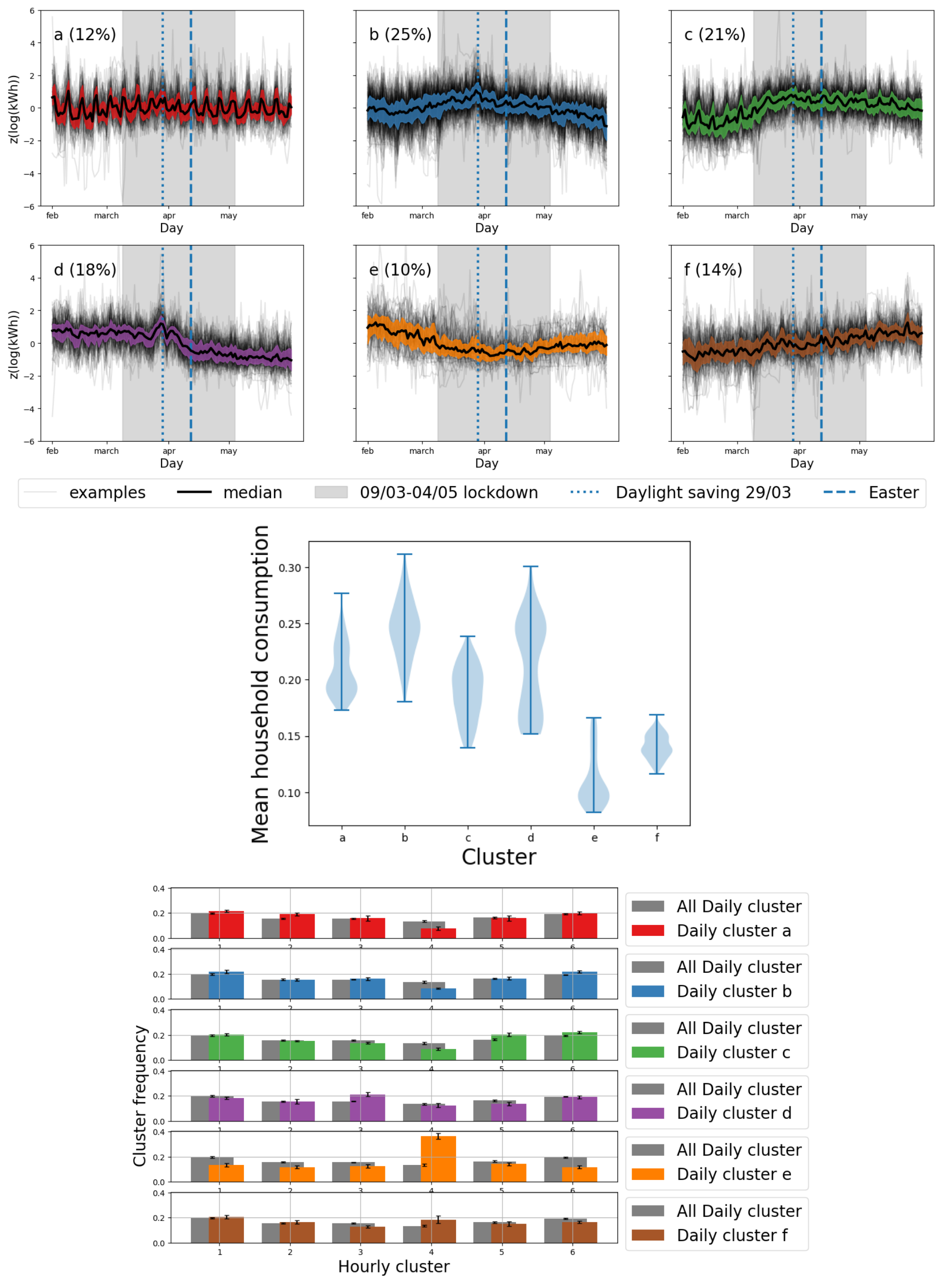


Figure 8: Daily consumption for the whole period February-May (year 2020).

Notes: **Top Panel:** Clusters obtained with k-means for the daily consumption over a period of a few months, for the year 2020. **Middle Panel**: Distribution of mean household consumption for consumers of each cluster in (a). **Bottom Panel:** For each daily cluster in (a), the distribution of hourly cluster (from Figure 6). The errors bars are the standard deviation obtained with a bootstrap procedure (10 re-sample, each with 60% of users).

For both 2019 and 2020, we have a cluster (cluster (d) for 2019, (a) for 2020) in which the difference between weekday and weekend is particularly evident and regular throughout the period. This cluster indicates people likely to not be so much at home during the week compared to the weekend; the same is probably valid also for the households in the cluster (a) for 2020 - despite the restrictions, some people where still going to work outside home.

For 2020 there is a peak around the beginning of the lockdown (cluster (b) and (d) synchronized with the Daylight saving date), followed by a decrease in consumption. Cluster (c) indicates probably household with people doing smart working, since the consumption has increased regularly with the first closures and then has continued to stay high. The information in Table 1 suggests a smaller surface than the average and high prevalence of green contracts, likely to indicate relatively recent electricity contracts, in a central area of the city. Cluster (e) has a lower level of consumption during the closure, and it is also the cluster with the minimum mean household consumption, as indicated in Figure 8, middle panel. It likely indicates houses where some tenants moved somewhere else during the lockdown, for example off-campus students. In fact looking at Table 1, households in cluster e are likely to be bigger than average.

Overall, the trends evident from the 2020 daily clusters are quite different from the cluster of 2019. For 2019, apart from Easter and the week-end regularity, clusters show some increasing or decreasing trends, probably related to seasonality through heating and cooling systems. For the 2020 instead, daily clusters allow to characterize groups of households based on their response to closure.

Finally, we associate daily and hourly clusters, to link the monthly behaviors with the daily patterns: we check for each households types a-f (years 2019 and 2020) if some daily clusters at hourly resolution are more prevalent than others; this analysis indicates different typical profiles of users throughout the pandemic lockdown.

In Figures 7 and 8, bottom panels, we show the different frequencies of hourly for Clusters 1 to 6 from Figure 6. For 2019, we underline how the regular week-day/week-end behavior of a household type (d) is associated with a prevalence of hourly cluster (2), the typical eight-hours-day-at-work behavior. For the year 2020, we notice how household type (c) (forced smart-working users) have a high prevalence of hourly behavior (5) and (6), describing late morning peak (behavior 5) and a high peak at lunch-time (behavior 6).

In this Section, we applied different clustering techniques to associate daily and hourly clusters of residential consumption throughout the period before, during and after the first Covid-19 lockdown in Italy. Broadly speaking, we are able to identify households that keep a similar regular pattern of consumption as before lockdowns, and others who switch to a working from home consumption patterns, with a strong increase in mid-day consumption peak.

The method proposed of linking clusters obtained with multiple time periods and resolution is a valuable approach that can be generalized for the analysis of natural experiments when a control group is not available.

3 Discusssion

While the Covid-19 pandemic has coincided with a temporary change in the power system's dynamics, prospects for a consolidated structural change are the greatest at the time of societal transformations. This natural experiment has provided a unique opportunity to study power systems that have coped with high RES under a situation where demand is low and there is significant overcapacity. The quantification of the impacts that this atypical shock has had on the hourly operations of power generators, on day-ahead power prices and on balancing costs can provide valuable insights. It is important to underscore that the extent by which the effects we have measured can be informative of the long-run development of power systems will depend on how the underlying mechanisms will hold up in a situation with high RES and normal (or higher) demand, and relatively little dispatchable supply. The models developed, capturing supply-demand effects based on current market conditions, should therefore be considered as a valuable empirical assessment shedding light on the current market dynamics, paving the way for new empirical analysis based on longer time series of data collected during the post-pandemic world, as well as for new model-based assessments and on political economy analysis of decarbonization.

When RES shares approached 80% in Germany, 70% in the UK and Spain, 60% in Italy and 40% in France, the power plants providing dispatchable generation responded very differently, depending on their marginal costs and capability to accommodate ramping requirements. The hourly profile of coal's capacity factor has been remarkably flattened due to the net-load shock. In Spain and Germany, both highly reliant on coal (i.e. with counterfactual shares in the dispatchable mix ranging between 15% and 20%), the observed share fell around 1% to 2% and 5%–7%, respectively ('temporary phase-out' category). In other cases, the net-load shock has forced only part of the fossil-based power plants to be cut out from the market, while part of it continued to operate, likely becoming the new marginal technology during peaks ('partial market exit' category). The need for flexible power generation was met through different sources across the power sectors analyzed ('increase in flexibility requirements' category): through an increase in the activation of hydropower, where available (Spain, Italy, Germany), or through flexible gas-fired plants (Italy, Germany and the UK). Finally, although partially hit by operational constraints, low-cost generation from nuclear sources fulfilled most of the remaining baseload requirements ('unaffected by market competition' category).

The sudden demand shock and the subsequent high RES penetration rate have reduced day-ahead prices by an extent ranging from 20% to 50% of counterfactual prices, once the effect of low fossil fuel prices is filtered out. The occurrence of negative prices in the day-ahead market in Germany and to a smaller extent in France and the United Kingdom, and of very high price spikes in the German balancing market, underscores the need for more flexibility in the European power system. Although rising in the UK and Germany, costs of balancing markets remained a small component of overall power system costs (generally below 2 € MWh^{-1} in France, the UK and Germany). On the other hand, the Italian costs of re-dispatch services, which include the costs incurred to adjust the schedules of RES to ensure that they are compatible with a secure operation of the grid, have increased substantially and reached values comparable or even higher than the daily wholesale prices. RES generation's impact on wholesale electricity prices was exacerbated by low net-demand, a condition that will likely be increasingly relevant in the coming years if power systems decarbonization is not coupled supply and demand flexibility evolving at a similar pace. While the conditions analyzed in this study arise from an unexpected, sudden shock, it still holds that these dynamics can be expected during times in which net demand and dispatchable supply do not match due to inflexibility. These conditions will be more likely to arise in the future as we shift from a fully dispatchable system where supply follows demand to one where an increasingly small share of supply is dispatchable and demand will (have to) become more flexible.

International power markets will likely play an increasingly important role, as we find considerable shifts in the distribution of hourly net imports compared to the 2nd quarters in 2017–2019. In Italy, for instance, a sharp reduction in power imports from abroad during the lockdowns was coupled by a milder shock to fossil fuel generation in the same weeks, compared to countries with a similar power mix (the United Kingdom and Spain). On the other hand, the French nuclear-based system was characterized by a shift towards increased exports. Our results suggest that as the EU power markets become more integrated, high RES penetration rates will lead to a situation in which the least efficient plants are not only dependent on national net-load but also interconnected net-load, as efficient dispatchable plants will be freed up to compete internationally (under the limits posed by interconnection capacity constraints). Nuclear, due to its inflexible nature, will likely play an increasingly large role in exports when RES is pushing net-load down in countries which have abundant capacity.

Whether power systems will phase-out or, on the contrary, fall in a lock-in of coal power plants may will not only depend on the profitability of wholesale markets, on cross-country markets' integration and on technical factors such as the degree of flexibility from high shutdown and restart costs, but also on market rules such as the presence of long-term contracts and capacity reserve mechanisms (Rentier et al., 2019). A stronger EU-ETS scheme (e.g. following a reduction in emissions allowances) may put further pressures on the viability of coal-fired power plants and the least efficient gas generators across Europe, tying power plants' marginal costs increasingly to their carbon intensity.

Our analysis underscores the need of powering up the grid infrastructure and ensuring additional flexibility from ancillary services. New real-time trading platforms for balancing resources among EU Member States, currently under development, would further lessen the stress on grid management operations and mitigate the frequency of very high bids for surplus and deficit imbalances. Our results call for new research into the effect of the low net demand experienced during Covid-19 lockdowns on ancillary services' costs, including curtailment of renewables, as we suggest that the lockdown periods can act as a good natural experiment. Aggregate monthly statistics display that during Covid-19 lockdowns ancillary services' costs increased not only in Italy, but also in other countries such as the UK. Furthermore, due to the lack of available data, we were unable to investigate the role of storage in response to the shocks induced by the pandemic. Including such aspects may provide further insight into power system characteristics that can enhance or limit the efficiency with which systems can deal with a fossil fuel price and demand shock in terms of financial, security and environmental performance.

References

Brijs, T., K. D. Vos, C. D. Jonghe, and R. Belmans (2015). Statistical analysis of negative prices in european balancing markets. *Renew. Energy 80*, 53–60.

Buechler, E., S. Powell, T. Sun, C. Zanocco, N. Astier, J. Bolorinos, and R. Rajagopal (2020). Power and the pandemic: exploring global changes in electricity demand during covid-19. 2008.06988.

Caldecott, B. L. and J. McDaniels (2014). Stranded generation assets: implications for european capacity mechanisms, energy markets and climate policy. Technical report.

Chen, S., D. Igan, N. Pierri, and A. F. Presbitero (2020). Technical report. WP/20/125 IMF Working Paper.

Cicala, S. (2020). Technical report. Tech rep (Accessed 6 May 2020).

Colelli, F. P., D. Witkop, E. D. Cian, and M. Tavoni (2021, May). Power systems' performance under high renewables' penetration rates: a natural experiment due to the COVID-19 demand shock. *Environmental Research Letters 16*(6), 064018.

den Bergh, K. V., J. Boury, and E. Delarue (2016). The flow-based market coupling in central western europe: concepts and definitions. *Electr. J. 29*, 24–9.

Felten, B., T. Felling, P. Osinski, and C. Weber (2019). Flow-based market coupling revised - part i: Analyses of small- and large-scale systems. *SSRN Journal*.

Figueres, C., C. L. Quéré, A. Mahindra, O. Bäte, G. Whiteman, G. Peters, and D. Guan (2018). Emissions are still rising: ramp up the cuts. *Nature 564*, 27–30.

Graf, C., F. Quaglia, and F. A. Wolak (2020). (machine) learning from the covid-19 lockdown about electricity market performance with a large share of renewables. *J. Environ. Econ. Manage. 105.*

McWilliams, B. and G. Zachmann (2020). Electricity consumption as a near real-time indicator of covid-19 economic effects. Technical report.

Murdock, H. E., D. Gibb, T. André, J. L. Sawin, A. Brown, F. Appavou, and L. Mastny (2020). Renewables 2020-global status report. Technical report.

Narajewski, M. and F. Ziel (2020). Technical report.

Prol, J. L. and O. Sungmin (2020). Impact of covid-19 measures on short-term electricity consumption in the most affected eu countries and usa states. *Iscience 23*.

Rentier, G., H. Lelieveldt, and G. J. Kramer (2019). Varieties of coal-fired power phase-out across europe. *Energy Policy 132*, 620–32.

Tranberg, B., O. Corradi, B. Lajoie, T. Gibon, I. Staffell, and G. B. Andresen (2019). Real-time carbon accounting method for the european electricity markets. *Energy Strategy Rev. 26*.

Weber, C. (2006). *Uncertainty in the Electric Power Industry: Methods and Models for Decision Support*, Volume vol 77. Springer.

Modelling the implications of smart working from home on buildings' energy demand

Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC),
RFF-CMCC European Institute on Economics and the Environment (EIEE)

February 2022

Abstract

The report evaluates the implication of working from home on buildings demand. Using the EDGE-WITCH modeling framework, it explores different scenarios of increased remote work in a post-pandemic world. The report uses data collected for the building sector from March 2020, to identify useful patterns. Results indicate that the energy demand impact of working from home is close to zero, due to the compensating effect of increased residential consumption and reduced commercial ones, and to disparities between developed and developing regions. Model outputs show net reductions centered around -1% for 2050, but with great variations across regions and net increases for the residential sector of about 2 to 5% and decreases for the commercial of about 8%. This analysis can help inform the future of building energy demand.

1 Introduction

Climate change constitutes one of the biggest challenges humanity has ever faced. Mitigation efforts imply a strong reduction in GHG emissions and require acting simultaneously on many sectors, with prioritizing criteria connected to the single sector contribution to total emissions.

Decarbonization of the building sector is indeed critical. Overall the sector accounts for almost 40% of total energy-related emissions, and improvements could contribute to mitigation goals in a cost-effective way. According to most models, the savings in energy costs typically more than exceed the investment costs (Pakere et al., 2020).

Up to now, however, registered emissions trends for the sector show persistent increments. Final energy demand in buildings rose by 1% from 2017. This trend sharply contradicts the world goals of yearly 7.6% emissions reductions, needed not to exceed the 1.5°C warming target. Moreover, the rate of improvement in sectorial energy intensity has also slowed down, reduced to half the average of the previous year from 2010 (IEA, 2019).

Building stock is set to double by 2050, with some studies pointing to increases in floor area of over 150% by half of the century, but this increase is not necessarily related to an increase in final energy consumption; according to GEA "efficiency" pathway heating and cooling energy uses could decrease of about 50% compared to actual level by 2050 if all energy savings measures were deployed. In a scenario where no energy savings policies are deployed, forecasts see increases in consumption of about 75% compared to 2010 levels, with some models projecting increases of over 150%. It is therefore clear the importance and urgency of adequate policies and regulations for the expanding building sector.

During the Covid-19 pandemic, the world registered a temporary reduction in total emissions of about 7%, which is in line with the required rate of decrease. However, rather than casting lights of optimism, this data unveils the extent in the magnitude of structural changes needed to stay successfully below IPCC target of 1.5°C warming target. Moreover, history shows the recurrence of energy-intensive recovery plans that are often deployed as economic stimulus after big-scale crisis events. More than ever now is required economic recovery efforts targeted to drive emissions down, mainly through the financing of high potential green investments. Even if the registered changes in emissions are entirely due to forced reductions in energy demand, the overall effect may provide quantitative indications of the potential impacts and limits that strong structural changes could deliver if persistent and implemented in the future. Working from Home (WFH hereafter) has the potential of being structurally adopted by countries all over the world in the near future, as demonstrated by multiple studies. The extent of disruptions caused by the pandemic affects not only the technical and energy demand sides but even more prominently involves behavioral aspects, induces legislative frameworks to adapt to new scenarios and has the potential to accelerate changes in the job market and economy sectors that were already taking place.

The main objective of this report is to establish to what extent scenarios of WFH could affect future energy consumption patterns and relative emissions of the Building Sector. WFH could have a "friendly" or a "damaging" contribution to carbon emission. The strict measures imposed by world governments forced billions of people at home, while industries and offices were closed. The increased number of people staying at home, translated into higher levels of residential building occupancy, and led to an increase in energy consumption. By contrast, the reduced presence of personnel in offices resulted in a net decrease of energy consumed by the commercial building sector.

If found to be overall energy saving, excluded others convenience parameters, WFH could be included among those measures that policymakers should favor in the coming years to comply with climate treaties. It must be highlighted that there is little or no literature published yet, that try to frame a world energy-Work From Home scenario as is done in this study.

2 Methodology

EDGE Building Energy Demand GEnerator Model was chosen as the modelling platform. EDGE is a bottom-up, statistically-based simulation model, which is multi-regional and allows for long-term projections. The model projects buildings energy demand across 11 regions, with a country-level implemented resolution for 28 European Union nations. It must be highlighted that most of the data available in the literature for the Building Sector derive from US and EU databases, and this fact justify the increase in resolution for EU.

EDGE is implemented with a 7 Energy Carriers resolution, that covers well the world's different building's energy portfolios. Electricity, traditional biomass, modern biomass (including pellets and improved fuelwood), coal, natural gas (also including biogas), liquids (including petrol, heating fuel oil and biofuels) and heat (district heating). In OECD countries, around 75% of Final Energy Demand is covered by Electricity (37%) and Natural Gas (38%), while in developing countries, the shares of the others fuels are higher.

EDGE does not model the Supply Side (generation) and therefore between sector interactions or feedbacks are not contributing to the results. The model projects which energy carriers will be adopted or discouraged in time accordingly to the SSPs narratives.

The fundamental structure of the EDGE model was maintained for the present study, while updates were made to enhance EDGE with the new correlations and variables needed for a WFH implementation. Nine principal variables were added and the model was upgraded to provide energy insights also for the commercial sector. First was identified the number of homeworkers around the world (WFH level) according to the narratives of 5 different SSP scenarios, and then modeled its evolution in the future with different methods. Then, correlations were established between WFH levels and energy consumption variations for the Residential and Commercial sectors.

There have been many attempts to measure the percentage of workers that fully operated from home during the pandemic. Dingel and Neiman (2020) and ILO (2020) provided a comprehensive review of those methods along with a methodology to calculate the work from home potential of countries in the world. The method adopted by Dingel and Neiman (2020) used occupational descriptions from the Occupational Information Network (O*NET) to estimate the probability for an occupation to be done remotely. To produce estimates for other countries than the US, a similar use of the US O*NET surveys was done for the International standard classification of occupations (ISCO). The final results showed a clear positive relationship between GDP per capita and the shares of jobs that can be done from home, as was also confirmed by Hatayama et al. (2020).

Based on Dingel-Neiman and ILO works, IEA (2020) estimates that around 20% of jobs globally could be done from home, with values ranging from 10% in Sub Saharian Africa to 45% in rich EU countries. A positive correlation between WFH potential and GDP cap is also identified. To transform an extensive variable, the share of teleworkable jobs from Dingel Neiman, into an intensive one, the number of home workers, and then make it projectable, “ETPr” Employment to Population Ratios were included. The ETPr index shows the percentage of working-age population, aged 15 to 65, actually employed. Once we obtained the number of workers for a specific geographical region in a year, we derived the number of Home Workers by multiplying with Dingel Neiman coefficients. ETPr were provided by World Bank while population projections by IIASA's World Population Program (Samir and Lutz, 2017). The two datasets were matched to produce as output five different SSP Shared Socioeconomic Pathways Work From Home penetration scenarios. Another method adopted consisted of an “upgrade” of the Dingel Neiman method, done by adding more variables to the WFH interpolation. The exploitation of the full potentials of the IIASA dataset allowed for a WFH calibration based also on educational and age profiles, following the recent evidence from World Bank. As modeled in this study, Work From Home depends therefore from GDP per capita, higher values leading to higher overall teleworkability, and from population composition and macro Labour Market structure.

To make the model functioning, data were collected for variations of both seven Energy Carriers, described above and five different End Uses. The EDGE architecture operates by defining five drivers of energy demand (End Uses): a) cooking; b) water heating; c) space cooling; d) space heating; e) appliances and lighting. They depend on socio-economic and climatic variables, such as income, population, population density, cold degree days (CDD) and hot degree days (HDD). Those variables were kept unaltered. Instead, changes were necessary for the End Use generating functions. The assumption is that Work From Home alters only End Use demands and not the underlying Energy Carrier mix. For the Residential Sector it was possible to identify specific WFH variations for each End Use, not so for the Commercial Sector.

Figure 1 presents how computations are performed in EDGE. Fundamentals drivers (income, population, population density, CDD, HDD) are used to project Floor Space Demand, which is in turn an important parameter of the model, as it is used to perform many calibrations and to project Final Energy Demand. Then Useful Energy Demand is projected, without yet considerations on the supply side. Lastly Energy Carriers Shares are projected and Final Energy Demand is calculated.

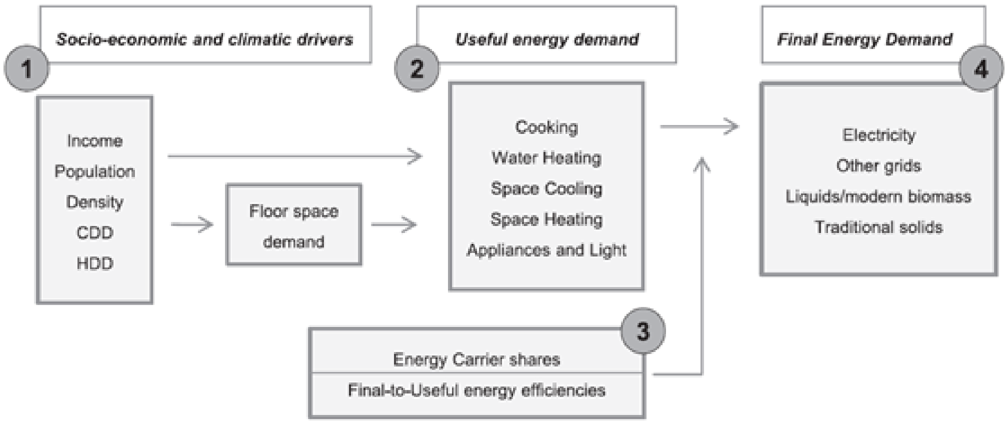


Figure 1: EDGE model logic flow chart

By applying both End Use and Energy Carriers variations to an End Use-Energy Carrier Matrix consistency was checked. This was necessary as reported increases in End Use consumption were mostly obtained by surveying or simulations, while Energy Carriers variations were more trustworthy because reported by energy providers themselves.

However, to develop accurate WFH scenarios, data were needed for increases of energy consumption specific per home worker. Cribb et al. (2020) tried to answer that question by analyzing domestic electricity and gas consumption profiles of 115'000 consumers, through access of their smart meters. We applied the same approach, which was tested and reproduced on a sample of 1'230 customers of a large scale multi-utility group-Italy and restricted on Electricity uses only. The two work weeks considered were the one from 24 to 28 February 2020 (Week1) and the one from 16 to 20 March 2020 (Week2). In Italy, the lockdown was in place from the 8th of March. Around 20% of clients were estimated to be in WFH with specific increases in electricity consumption ranging from 1 to 2 KWh, equal to about 15%. Another method adopted instead pointed to higher increases in consumption, between 25 to about 35%.

3 Main Results

This section discusses the results of a Monte Carlo simulation, with the number of runs set to an optimal value of 60. Across all 5 SSP scenarios, net variations due to WFH are projected to be slightly negative by 2050, with more pronounced trends by the end of the century (Figure 2 and Table 1).

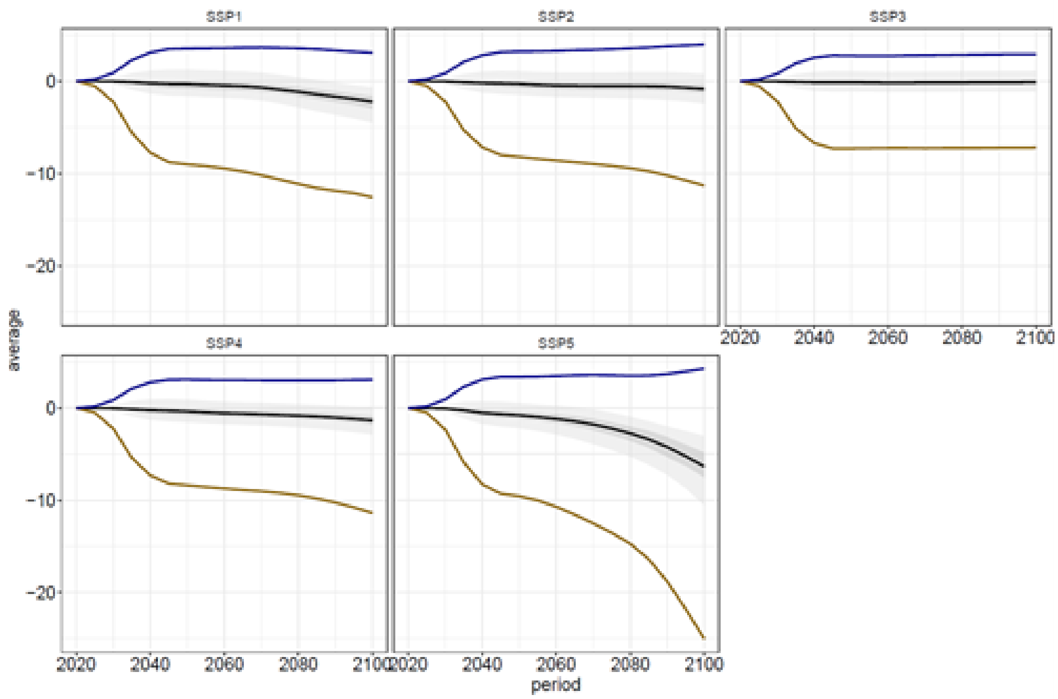


Figure 2: Final Energy variations. Net % change.

Notes: Brown line is for commercial, Blue line for Residential, Black is the net energy. Monte Carlo 60 simulations.

In all scenarios, final residential energy is expected to increase by 2050 from 2% to 5%, while final commercial energy to decrease of around 8%, with the most significant reduction prospected in a SSP5 scenario "Fossil-fueled Development", particularly if extended up to 2100. WFH should therefore impact globally, at net near zero (-2%) by 2050, considering the building sector as a whole, due to the compensation effect between commercial and residential sector (in line with available literature).

Scenario	2050	2100
SSP1	0 (-1 to 1)	-2.5 (-5 to 0)
SSP2	0 (-1 to 1)	-1 (-2 to 1)
SSP3	0 (-0.5 to 1)	0 (-5 to 0.5)
SSP4	0 (-1 to 1)	-1 (-5 to 0)
SSP5	-1 (-1 to 0)	-5 (-10 to -3)

Table 1: Final Energy variations. Net % change.

Strong differences appear in the magnitude of changes between developing and developed countries (Figure 3).

Figure 3: Final Energy variations. Net % change.

Notes: Net % change for all EDGE Regions. Monte Carlo 60 simulations.

Results indicate that global-net zero is reached through a compensation between their relative variations, with developing regions being expected to increase final energy use. This is due to a substantial rise in residential cooling demand due to improvements in income per capita and an increase in temperature at mid-latitudes induced by climate change.

In all scenarios, particularly in the SSP4 "Inequality" and in SSP3 "Regional Rivalry" developing countries show net variations near zero or slightly positive, while developed countries display net reductions of around 3% by 2050. This trend is mostly caused by the higher shares of Residential End Use in Developing countries, due to lower commercial penetration and climatic differences.

A breakdown of Deltas by End Use and Energy Carrier highlights the net positive contribution of Cooking and the strong negative one of Appliances and Lighting (Figures 4, 5 and 6).

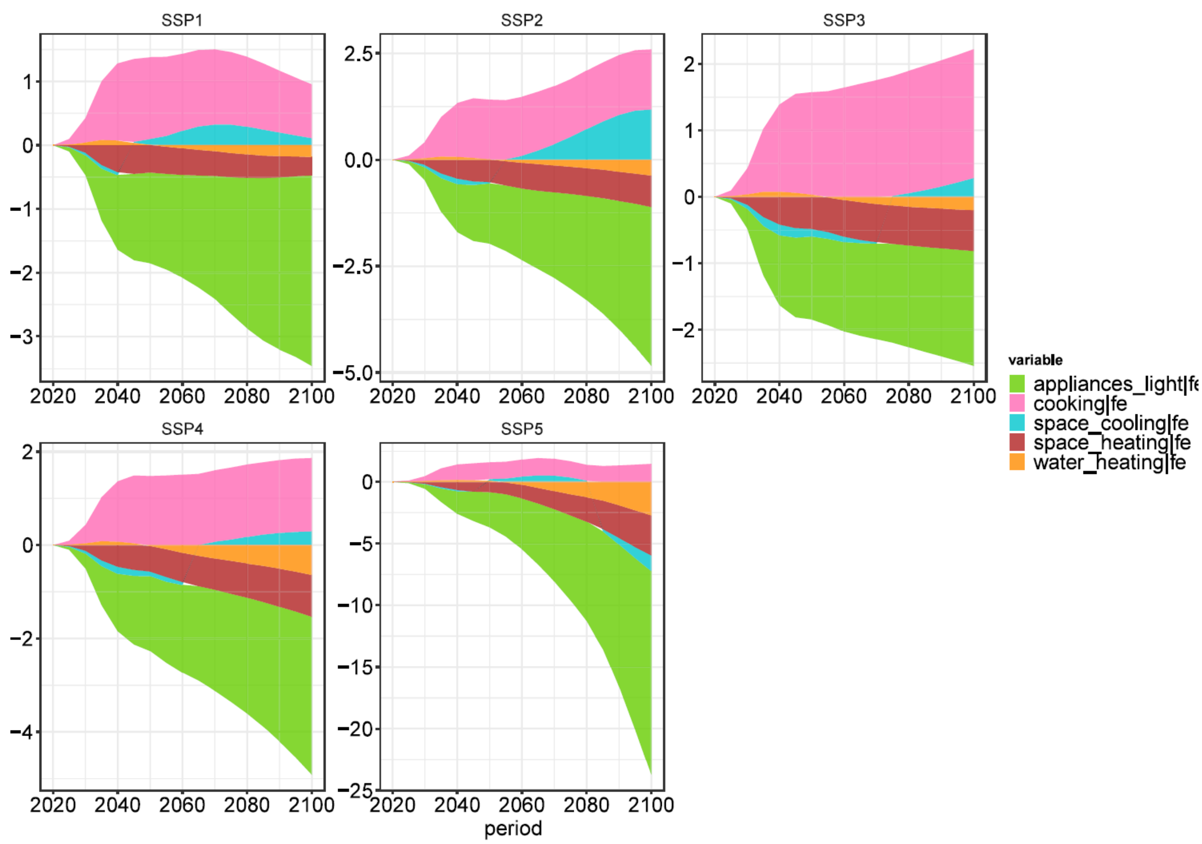


Figure 4: Final Energy variations (EJ/Yr). End Use deltas

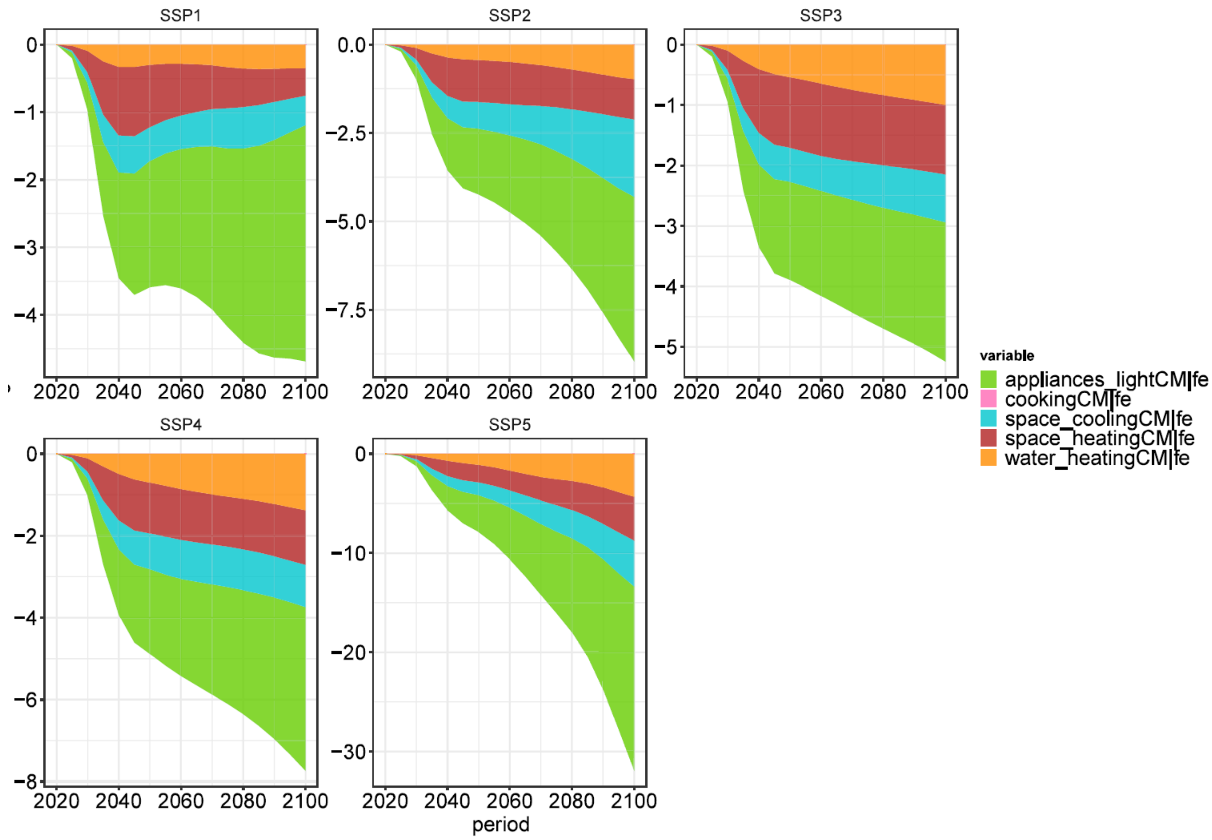


Figure 5: Final Energy variations: Commercial Sector (EJ/Yr). End Use deltas

The former due to its unique presence in the Residential Sector while the latter due to its prevalence in the Commercial sector. Space Cooling share in the residential sector is projected to increase constantly throughout the century in developing countries, and therefore its contribution span between slightly negative to positive values from around the 50's.

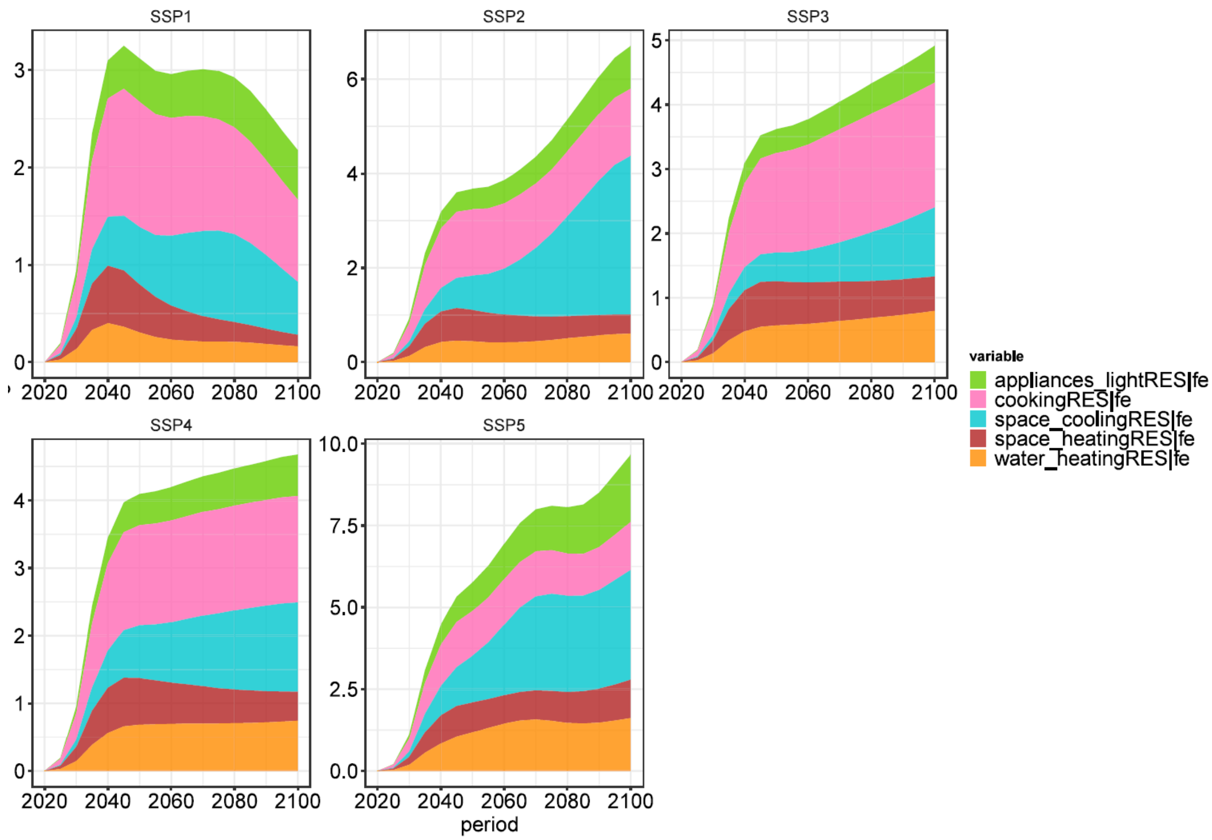


Figure 6: Final Energy variations: Residential Sector (EJ/Yr). End Use deltas

Lastly, we considered an extreme case of a global Lockdown COVID-19 scenario (Figure 7). Results showed reductions for the commercial sector of around 20% and increases for the residential sector of around 10%, leading to a net increase of final energy required by the building sector of 0 to 5%.

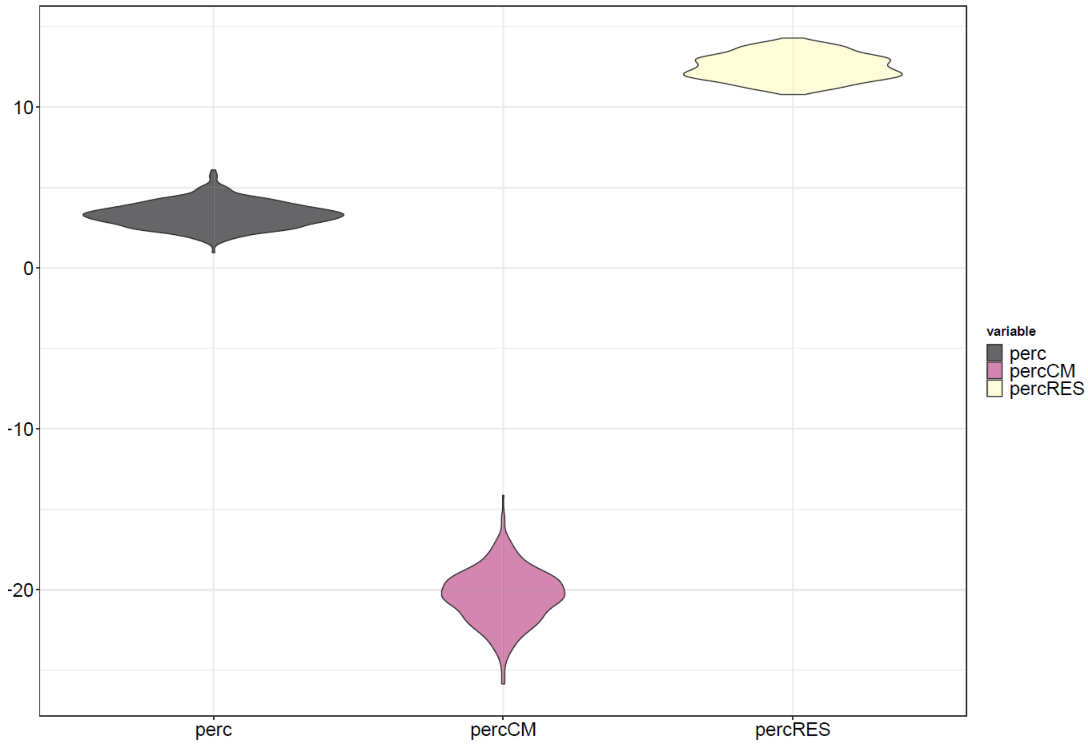


Figure 7: Simulation for COVID-19. Final Energy by enduse

These numbers are comparable with the ones provided by Forster et al. (2020) and Le Quéré et al. (2020), that indicate commercial reduction in emissions of 20 to 50% and residential increases of 10 to 20%. This provides confirmation of the accuracy of the calibration.

Overall, these results provide insights for thinking about future scenarios of energy demand in the building sector which account for change of habits and technology. A natural extension of the work should include the transportation sector. Although transport is not included in EDGE it could contribute to significant energy and emission reductions as commuting is reduced due to WFH. IEA (2020) estimates avoided CO2 emissions due to less commuting being 3.6 times greater than those incremented in the residential sector. If this contribution was to be artificially included in the model, net savings could reach 4 to 5% by 2050.

4 Discussion and Conclusion

This report is intended to answer whether WFH could be a valid option for policymakers to reduce Building sector energy consumption in the coming decades. The findings cannot provide a clear picture at the regional level, disregarding climatic patterns and general economic frameworks of the analyzed country. At the global level, instead, results confirm the evidence of previous studies of almost net-zero impacts of WFH on the Building sector. Yet, this research offers new insights on the dynamics contributing to net-zero energy savings. The balancing effect between commercial and residential sectors was widely expected. On the contrary, the one between developing and developed regions was less predictable.

Developing regions are expected to experience a strong rise in residential cooling demand, due to improvements in income per capita, but also to Climate Change induced increase in temperatures at mid latitudes. This strong increase is particularly evident in the first half of the century, and the projected increase in commercial floor demand is still not sufficient to balance it. Also, despite WFH potential being lower for developing regions, its share of WFH on total population is higher. This happens as their populations are younger and so the shares of people aged 16 to 64. Hence commercial energy reductions for developing regions are lower (being dependent on the unoccupancy levels of workplaces) while residential reductions depend on the WFH-total population and are therefore unaffected by the lower WFH potentials.

These effects contribute to higher overall residential increases and lower commercial reductions in developing regions, while the contrary happens in developed ones.

An increase in Cooking End Use of about 50% per Home Worker contributes along with Space Cooling to the residential increase both in developing and developed regions. At an energy carrier level, this implies greater consumption of biomass and oil in the former and of natural gas in the latter. Also, as improvements in the energy ladder take place in Africa, India etc., natural gas and electricity for cooking gradually substitute inefficient EC.

Yet, the convenience of the adoption of WFH largely depends on energy savings in the transportation sector, as most studies suggest. Also, developing regions may result from this research less benefited from WFH, at least in the short term and with a focus on the Building sector. However, road congestion issues in countries like India are major problems that strongly affect business and life quality. The adoption of WFH has therefore the potential to impact greatly, and in a positive way, in sectors not considered by this research.

The adoption of more efficient appliances in the residential sector due to WFH is also possible. As some studies indicate, residents give more importance to gas and electricity bills reductions when they start to work from home. Higher interests in installing solar panels and in the use of renewables were also registered by the research.

On the contrary, rebound effects such higher use of appliances not directly related to WFH or increased miles per worker a day due the moving of WFH workers outside cities were registered by other studies. Also, telework facilities are becoming an option, for those workers who still feel the need for social interactions.

The results of this research on the Building Sector, and the considerations above, seem to suggest that overall global strong improvements in energy savings are difficult to reach by adopting WFH. Many counteracting forces are in place within countries (between residential and commercial sectors) and across regions. Also, several cascade effects (increased residential floor area per capita, telework facilities etc) tend to null each other and the overall contribution. At a regional level, developed regions may achieve net savings (in the Building sector) of about 1 to 5% over the century, while developing regions changes from -2 to +2%, according to the SSP scenario. The (extreme) SSP5 scenario is the most optimistic one, and foresee net savings in the Building sector due to WFH of about 5% by 2100 for developing regions, and of 10% for developed ones.

References

Cribb, J., I. Gotlibovych, and D. Sykes (2020). Domestic energy usage patterns during socialdistancing.

Dingel, J. I. and B. Neiman (2020). How many jobs can be done at home? *Journal of Public Economics 189*, 104235.

Forster, P. M., H. I. Forster, M. J. Evans, M. J. Gidden, C. D. Jones, C. A. Keller, R. D. Lamboll, C. L. Quéré, J. Rogelj, D. Rosen, C.-F. Schleussner, T. B. Richardson, C. J. Smith, and S. T. Turnock (2020, October). Current and future global climate impacts resulting from COVID-19. *Nature Climate Change 10*(10), 913–919.

Hatayama, M., M. Viollaz, and H. Winkler (2020). *Jobs' Amenability to Working from Home: Evidence from Skills Surveys for 53 Countries*. Policy Research Working Papers. The World Bank.

IEA (2019). Global status report for buildings and construction 2019, towards a zero-emissions, efficient and resilient buildings and construction sector. Technical report.

IEA (2020). Working from home can save energy and reduce emissions. but how much? Iea commentary.

ILO (2020). Working from home: Estimating the worldwide potential. International labour organization policy brief.

Le Quéré, C., R. B. Jackson, M. W. Jones, A. J. P. Smith, S. Abernethy, R. M. Andrew, A. J. De-Gol, D. R. Willis, Y. Shan, J. G. Canadell, P. Friedlingstein, F. Creutzig, and G. P. Peters (2020, July). Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. *Nature Climate Change 10*(7), 647–653.

Pakere, I., D. Lauka, and D. Blumberga (2020). Does the balance exist between cost efficiency of different energy efficiency measures? dh systems case. *Energies 13*(9), 11–16.

Samir, K. C. and W. Lutz (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change 42*, 181–192.

Report Summary of the Synthesis working group (WG3) within the EDITS community work and participation to other WGs

Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC),
RFF-CMCC European Institute on Economics and the Environment (EIEE)

February 2022

Synthesis working group

Massimo Tavoni, together with Shonali Pachauri, are responsible for the Synthesis working group (WG3). A proposal was presented at the EDITS meeting which took place before summer. The WG proposal included the development of boundary conditions to the scenarios (e.g. revised socio-economic drivers), and the analysis of the EDITS scenario output along the feasibility multi-dimensional approach developed by IIASA and CMCC.
https://iopscience.iop.org/article/10.1088/1748-9326/abf0ce
Meanwhile, the development of the narrative WG proceeded. Thus, during the December annual meeting it was decided that the synthesis WG should focus on evaluation metrics based on advanced welfare frameworks, and that the feasibility approach should consider historical parallels not just with the energy technologies but others as well, and that the option level feasibility approach of AR6 should be considered for EDITS as well. Below a description of the activities of WG3 and envisaged outputs.

General Working Group description

1. Overall aims of the Working Group: To synthesize the work carried out in the other WGs and summarize the main insights of the project, specifically in terms of (i) defining boundary conditions (e.g. demographics, economic convergence) which are input to the models and their coherence with the LED narratives, and (ii) evaluating the output of LED scenarios through developing and applying a multi-dimensional framework

2. Key expected input from others in the long-run: Summary articles on EDITS scenarios and analyses of the EDITS database

3. Key expected outputs that feed into other Working Groups: Connections to WG Narratives, but since this is the last one it will mostly receive inputs from other WGs

Results and roll-over in 2021

1. Key activities/achievements in 2021: Presentations at meetings, participation in other WGs (Building, Industry, Data, Narratives)

2. Activities and foreseen outputs that roll-over to 2022: Definition of multi-dimensional welfare dimensions to be used in the ex post assessment of the EDITS scenarios

Annual Plan 2022

1. The scientific goal/research question for 2022 (also consider the cross-cutting themes, currently proposed as digitalization, equity, lifestyles/behavior): To select an appropriate multi-dimensional welfare/ feasibility framework for evaluating low energy and material demand scenarios.

2. Foreseen product(s) of 2022: Review welfare approaches and feasibility concepts (including the ones proposed in IPCC AR6) and identify their usefulness and needed adjustments for their application to the EDITS ensembles

3. Methods to be used (including expected input from other Working Groups): Expert assessments, statistical approaches, welfare economics

4. Timeline (if relevant, indicate regularity or planning for meetings): Dependent on other WGs progress, but plan to have a first proposed evaluation framework by mid-2022.

5. Interaction with other Working Groups: All, especially the Narratives one.

6. Members and roles:

   (a) Co-leads: Shonali Pachauri and Massimo Tavoni

   (b) Cross-cut referees

      i. Cross-cut theme digitalization: Elena Verdolini/ Greg Nemet/ Charlie Wilson

      ii. Cross-cut theme equity: Diana Urge Vorsatz/Arnulf Grubler/Narasimha Rao

      iii. Cross-cut theme lifestyles/behaviour: Oreane Edelenbosch/ Leila Niamir/ Felix Creuzig

   (c) Other roles (e.g. liaising with specific other WG)

      i. Liaise with Arnulf Grubler/Charlie Wilson/Greg Nemet from the Scenario Narratives WG

ii. Liaise with Bas van Ruijven/ Masa Sugiyama from the Scenario Protocol WG
iii. Liaise with sector WG leads for Buildings, Transport and Industry

Other working groups

Working Group 1 – Industry

CMCC was also involved in other WGs. In particular, Elena Verdolini participated in the Working Group 1 – Industry. She contributed to the EDITS output on innovation dynamics (together with G. Nemet, lead, and Leila Niamir). The report will be submitted as a deliverable for EDITS. Elena was responsible for the case study on additive manufacturing (aka 3D printing) and contributed to the set-up of the analysis framework, as well as the conclusions. Elena was also involved in the following activities: EDITS industry group, focusing on the survey of econometric results to inform industry modelling of low energy demand scenarios, and the data group, to whose meetings she took part regularly. In addition, Elena submitted, together with others, two applications for sessions to the IIASA scenario forum: one on innovation with Greg Nemet and Leila Niamir, and one on digitalization with Charlie Wilson and Felix Creutzig.

Working Group 1 – Buildings

Giacomo Marangoni participated in the Working Group 1 – Buildings and was involved in a review paper on mapping building demand-side models as part of the output of the WG1. The paper, led by Alessio Mastrucci, Leila Niamir and Benigna Boza-Kiss, is entitled "Modeling social, behavioral, technological, and infrastructural innovations for reducing energy demand in buildings". For the paper, Giacomo is contributing on sections related to smart-meter deployment and behavioral interventions for energy conservation. Giacomo also prepared the survey used to inform part of the paper. The survey is instrumental to collect detailed information about buildings energy demand models, providing details regarding the EDGE-Buldings model.

Energy Consumption and CO_2 Emissions in China's Iron and Steel Industry: Potential Applications of Hydrogen Energy

Research group of OU Xunmin
2022.2.28

Abstract

As the economy develops and urbanization advances in China, China's iron and steel output and sales are growing rapidly, accounting for half of the world's iron and steel production capacity. Additionally, the iron and steel production process, featuring high energy consumption and high emissions, renders the low-carbon development of the iron and steel industry particularly important for China to achieve its self-imposed emission reduction goals. China's iron and steel industry has not only the advantages of fast development, a quick process iteration and good prospects but also the deficiencies of poor centralization, poor specialization and high costs. Such deficiencies offset efforts made to reduce emissions from iron and steel benchmark enterprises, resulting in the average energy consumption and carbon emission levels of China's iron and steel industry being on par with world average levels. China's iron and steel industry needs to undergo low-carbon development while solving such deficiencies. The carbon emissions of China's iron and steel industry have grown by a factor of approximately 7 between 1990 and 2020, reaching 1.81 billion tonnes of CO_2 in 2020. The emissions are mainly contributed by the long-process steel-making process.

Judging from the overall structure of the iron and steel industry, iron and steel production can be mainly divided into two categories, long-process steel making and short-process steel making. Short-process steel making omits the three highly energy consuming and highly polluting processes of sintering (pelletizing), coking and using a blast furnace, which greatly reduces material consumption, energy consumption and carbon emissions. In 2018, China produced 108 million tonnes (Mt) of crude steel via short-process steel making, of which steel produced using electric arc furnaces (EAFs) accounted for 11.6%. This percentage is lower than that for other major iron and steel producing countries and is thus objectively considered a reason for the high emissions of China's iron and steel industry. China's iron and steel industry is constrained by electricity costs and lower amounts of steel scrap. It is difficult to promote short-process steel making rapidly and its strategic value is limited in the short run, but faced with the risks of excess capacity, excessive inventory, industrial transfer and contraction of international trade, short-process steel making is of strategic importance and should be developed. It is estimated that China's iron and steel demand will peak between 2025 and 2030, and decline afterward. If iron and steel substitution is promoted in industries such as the

construction, machinery and automobile industries, China's iron and steel demand is expected to reduce by 30% by 2060.

Judging from the technical measures for low-carbon development of the iron and steel industry, both consumption and production ends have room for improvement. The consumption end can improve the utilization efficiency of iron and steel and stimulate the structural optimization of the iron and steel industry through improving product design, realizing material substitution and promoting recycling and reuse. First, the production end improves the production efficiency in each step of the iron and steel production process with the help of many new technologies and much new equipment. Research on the marginal cost of emission reduction of these process improvement technologies suggests that new technologies for (i) waste heat/residual gas recycling and reuse and (ii) steel loss reduction are cost-effective and can provide economic benefits when reducing emissions, and they are thus worthy of priority promotion. Second, carbon input and output are reduced via technical means, mainly through the technologies of carbon capture, utilization and storage. Third, centering on new production methods such as direct reduction iron making and smelting electrolysis technology, the production path of the iron and steel industry has been fundamentally transformed. Countries around the world have established demonstration projects and made important achievements.

Among many technologies in the iron and steel industry, hydrogen-energy steel making is one of the few technical options available for realizing the zero-carbon development of the iron and steel industry. Hydrogen-energy steel making is a clean and efficient technology in that it reduces material consumption and carbon emissions, but it requires the development of new steel-making equipment and the solving of problems relating to materials, design and safety. Meanwhile, the emission reductions of hydrogen-energy steel making depend on the choice of the hydrogen production mode. Once the problems of various technical links in the hydrogen supply chain are fully solved, hydrogen-energy steel making using hydrogen supplied from renewable energy sources has the potential to reduce emissions by more than 80%.

A scenario analysis suggests that in the scenario of conservative technology promotion, with a declining crude steel demand and increasing use of EAFs, the iron and steel industry can achieve a 64% emission reduction in 2060 relative to 2020, but there remains a gap to the goals of a carbon peak and carbon neutrality. Furthermore, it is difficult to fully absorb steel scrap resources in this scenario, which may cause waste. If the use of the EAF is vigorously promoted instead of hydrogen-energy steel making technology, emissions can be reduced by 63.1~72.2%, but the rapid promotion of EAFs may lead to a small increase in total emissions in the life cycle over a period of time, thus reducing the cumulative emission reduction benefits. There is thus a need to make dynamic decisions on the promotion of EAFs in combination with the actual utilization of renewable energy and steel scrap resources in China in the future. The use of hydrogen combined with the use of steel scrap and EAFs is expected to realize emission reductions of 85.4% to 88.9% in 2060, along with the best cumulative emission reduction.

The results of analysis suggest that China's iron and steel industry improve its overall management at production and consumption ends, promotes the research and design and popularization of process improvement technology, and prepare for steel scrap recycling and short-process steel making in the short term and develops carbon capture, utilization and storage and hydrogen-energy steel making technology, conducts theoretical research, strategic analysis and construction planning, and promotes the adjustment of the national energy system in the long term, so as to achieve near-zero emissions.

Key words: iron and steel industry, iron and steel demand, hydrogen energy application, greenhouse gas emission, technology development strategy

1. Introduction

1.1 Overall characteristics of China's iron and steel industry

As one of the largest industrial sources of CO_2 emissions, the iron and steel industry accounts for approximately 25% of direct greenhouse gas emissions from the global industrial sector and approximately 7% of the total direct emissions. Through industrialization and urbanization, China's iron and steel output has grown rapidly and is expected to continue to do so for some time. As shown in Figure 1, the output of iron and steel increased rapidly before 1975 and leveled off between 1975 and 2000, during which time the annual output of crude steel remained between 7 and 8 Mt [1–4]. The economic growth resulting from the reform and opening up of China has made China the main driving force for the growth of iron and steel output in the 21st century. Since 2012, China has accounted for more than 50% of the global output of iron and steel, with China’s crude steel output growing by 6% to 8% annually between 2017 and 2019. In 2020, thanks to infrastructure projects designed to help the economy recover from the COVID-19 crisis, China's crude steel output rose by 5% to 1.064 billion tonnes. Accordingly, China's iron and steel industry makes up 15% of China's total greenhouse gas emissions and is a major carbon emitter for both China and the world [1, 5]. Furthermore, the traditional process of producing iron and steel, featuring high energy consumption, high emissions and difficulty in reducing emissions, makes the low-carbon development of the iron and steel industry difficult. It will thus be challenging for China to realize its goals of a carbon peak and carbon neutrality.

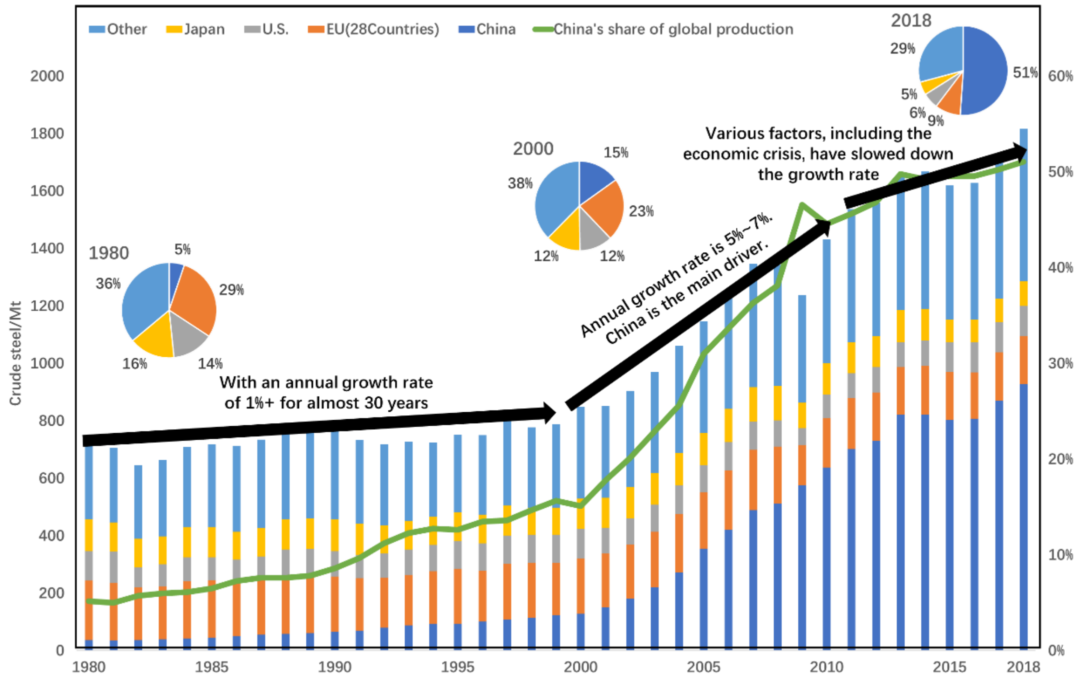


Figure 1. China's crude steel output and its global share

Figure 2 presents the import and export of raw materials and finished products for China in 2018. In 2018, China's crude steel output amounted to 928 Mt, marking an annual growth rate of 6.6%, whereas the consumption of crude steel was 871 Mt, with the remaining 57.43 Mt (accounting for 6.19% of the total output) being exported; i.e., the vast majority of steel output by China was consumed in China [6]. In the same year, China imported 10.64 Mt of iron ore, marking 58% of its total iron ore consumption, mainly from Australia (6.79 Mt), Brazil (2.34 Mt), South Africa (410,000 tonnes) and India (150,000 tonnes). If considering the iron content in iron ore, China's comprehensive external dependence on iron ore exceeded 85%; i.e., China has relied heavily on imports [7, 8].

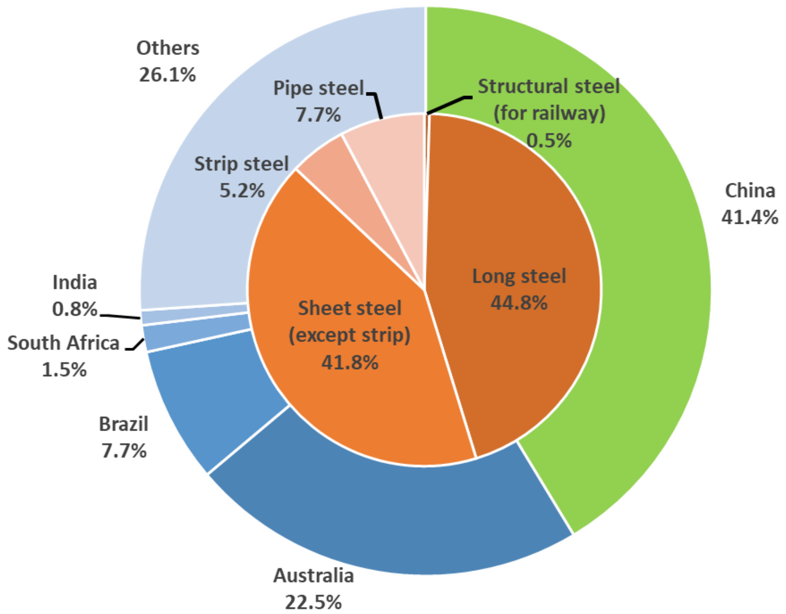


Figure 2. Sources of iron ore and destinations of finished steel in China in 2018

In terms of energy consumption and emissions, as a representative of industries that face difficulty in reducing emissions, the iron and steel industry consumes energy mainly sourced from coal, coke, the grid and natural gas. In 2015, China's iron and steel industry consumed 639.51 Mt of standard coal, accounting for 14.9% of the total national consumption, with coal and coke making up approximately 89.9% and electricity and natural gas making up approximately 10.1%. In the last 10 years, China's iron and steel industry accounted for 14.9% to 19.4% of the total energy consumed in China, with the annual average being 16.6%. As the industrialization and urbanization of China continues, the energy consumption of the iron and steel industry and the consequent pressure from greenhouse gas emissions may further increase [9].

China's iron and steel industry has the following advantages.

(1) The industry is developing rapidly. The annual output of China's iron and steel industry has ranked first in the world for several consecutive years. Currently, China's iron and steel industry produces and smelts more than 1000 steel grades and rolls and processes more than 40,000 products having different specifications. At the same time, the quality qualification rate of the products has reached 85%, complying with international standards, and some products have reached the advanced international levels of similar products.

(2) The production process iterates quickly, and the adopted steel-making technology is at an advanced international level. The technical level of China's iron and steel industry is constantly improving, which is reflected in the continuous elimination of backward technologies and old equipment. The most obvious example is that the steel-making technology of the open hearth furnace is no longer used by the vast majority of iron and steel enterprises in China.

(3) China's iron and steel industry has good prospects. The industry mainly benefits from the continuous development of China's economy and the recovery of the global economy, where the national macroscale control of the iron and steel industry plays a vital role.

Meanwhile, the following deficiencies offset efforts made by China's iron and steel benchmark enterprises to reduce emissions through the use of superior steel-making technology, such that the average energy consumption and emission levels of China's iron and steel industry is only comparable to the world averages.

(1) The centralization of China's iron and steel industry is poor and far from meeting the requirements of economies of scale. Approximately 40 steelmakers in China produce more than 1 Mt of steel a year each, whereas steel production in France is almost entirely covered by Usinor. This shows that compared with the situation in developed countries, iron and steel production enterprises are insufficiently concentrated in China. The competitiveness of China's iron and steel industry on the world stage is restricted to some extent by such a low concentration of iron and steel enterprises.

(2) The specialization of China's iron and steel industry is poor. Presently, China's iron and steel enterprises tend to cover a wide range of products and have various profiles accordingly, they fail to create their own competitive products, and their degree of specialization in product production is poor, leading to unclear specialization at the national level. In contrast, there is often clear specialization of production in large categories of products at most iron and steel enterprises of developed countries. The backward technology and equipment and poor concentration and specialization of China's iron and steel industry have caused serious problems, such as the low productivity and high cost of China's iron and steel products.

(3) Not only is the quality of iron and steel produced in China inferior to that of iron and steel produced in developed countries but also China is at a huge cost disadvantage relative to developing countries. At present, China's per capita steel output is no more than 32% of the world average level, the required man-hours per tonne of output in China is 6 times that in developed countries, and China has no competitive advantage over developed countries in terms of production costs.

In summary, China's iron and steel industry needs to consider domestic production/consumption, import and export trade and the characteristics of the industry in avoiding high costs of emission reductions and industry risks while achieving emission reduction goals.

1.2 Iron and steel production processes and emission reduction strategies

Figure 3 presents special equipment and various procedures required in iron and steel production, including those relating to raw material mining and processing, sintering, pelletizing, coking, iron making, steel making, steel rolling and public auxiliary systems. According to the technical category and raw materials, there are four main furnace processes: the blast furnace (BF) and basic oxygen furnace (BOF) process, the scrap electric arc furnace (EAF) process, the direct reduction iron (DRI) and electric furnace process and the smelting reduction (SR) and converter process.

BF-BOF and scrap-EAF technologies are used in leading steel-making processes. In the BF-BOF process, coke reacts with sintering ore/pellets in a BF to form hot metal and then decarbonizes with waste heat in a BOF (or EAF) to produce crude steel [10–12]. In the scrap-EAF process, treated iron scrap/steel scrap reacts directly in an EAF to form crude steel. This method omits sintering (pelletizing), coking and the BF [13–15]. However, these two technical routes require metallurgical coal and steel scrap/iron scrap resources. Iron and steel manufacturers thus use alternative processes, such as the DRI-EAF and SR-BOF processes, so as not to use these valuable resources [16]. The DRI-EAF process is mainly the reduction of iron ore to solid DRI, which is not only mainly used in the EAF but also used as an additive of the converter. Pellet ore is used in the DRI-EAF process, and solid (coal) and gas (e.g., natural gas, syngas and hydrogen) reducers are used [16, 17]. More than 75% of DRI is produced in a shaft furnace using a gas reducer, but if hydrogen is used as the reducer, it is likely that the iron and steel industry can realize ultra-low greenhouse gas emissions [18, 19]. The production of hot metal at high temperature through the reaction of ferrous materials with non-coking coal is called SR iron making. The advantage of this method is that non-coking coal, fine ore and dust can be used, but the disadvantages are that the energy consumption is higher than that of a BF and that it is difficult to directly reduce the emission of greenhouse gases [20, 21].

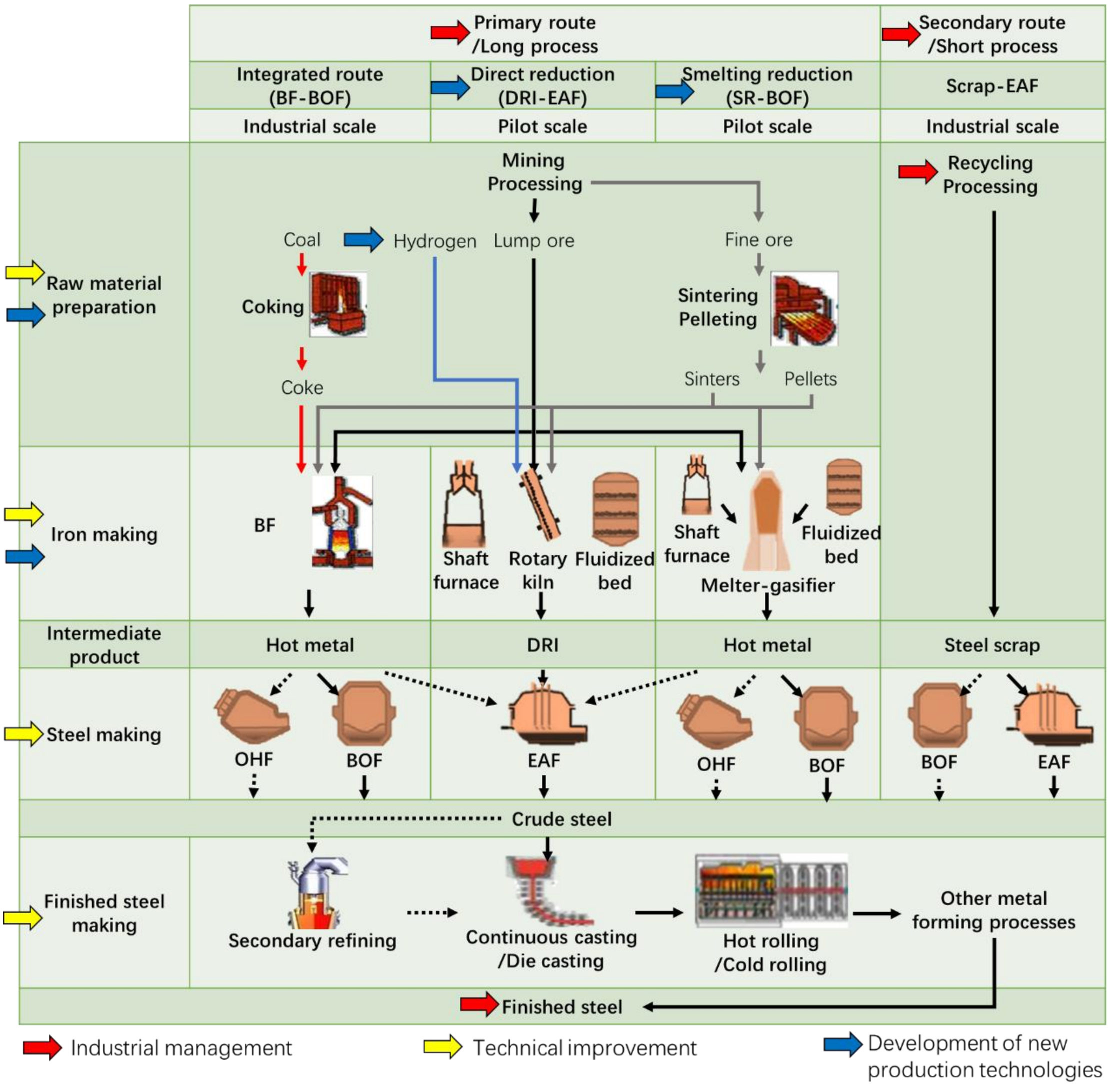


Figure 3. Typical steel production processes and corresponding emission reduction strategies

According to the production process, there are three main approaches for reducing the emission of greenhouse gases in the iron and steel industry (as indicated by the colored arrows in Figure 3). First, from both supply and demand sides, management methods should be optimized to reduce the loss of raw materials and energy. Second, for BF-BOF and scrap-EAF processes, which are the two most important iron and steel production processes today, technical improvements should be made for all links in the industrial chain, focusing on increasing the metallic yield, energy utilization rate and residual gas/heat recovery and utilization rate. Third, the research and design and promotion of ultra-low emission steel making technologies, such as hydrogen-based DRI-EAF and carbon capture, utilization and storage technologies of an iron and steel plant, can radically reduce carbon emissions. Since China proposed its goals of a carbon peak and carbon neutrality, the benefits of the first two emission reduction measures have been limited, and the technology of ultra-low-emission steel making has become even more important.

According to the source of raw materials, iron and steel production processes can be divided into long and short processes; specifically, BF-BOF, DRI-EAF and SR-BOF processes are long whereas the scrap-EAF process is short. Short-process steel making omits the three highly energy consuming and highly polluting processes of iron ore agglomeration (sintering/pelletizing), coking and using a BF, thus greatly reducing material consumption, energy consumption and carbon emissions [22–26]. Compared with other countries that produce crude steel, such as Italy (81.57%), the United States (68.01%) and India (54.78%), China (108 Mt, 11.6%) has a lower EAF steel-making ratio (Figure 4) and its crude steel is mainly used for high-end specialized steel products. It has been reported that for every tonne of steel produced, the BF-BOF route emits 2.15 tonnes of CO_2 whereas the scrap-EAF route only emits 0.15 tonnes of CO_2. In this case, the low proportion of short-process steel explains the high energy consumption and emissions of China's iron and steel industry. Furthermore, as steel scrap only accounted for 38% of EAF raw materials in 2018, hot metal still made up the majority of EAF raw materials [37]. However, the high costs of steel scrap and electricity, as well as practical factors such as the steel scrap output and recovery potential, make it difficult to directly and quickly replace long-process steel making with short-process steel making [27–29].

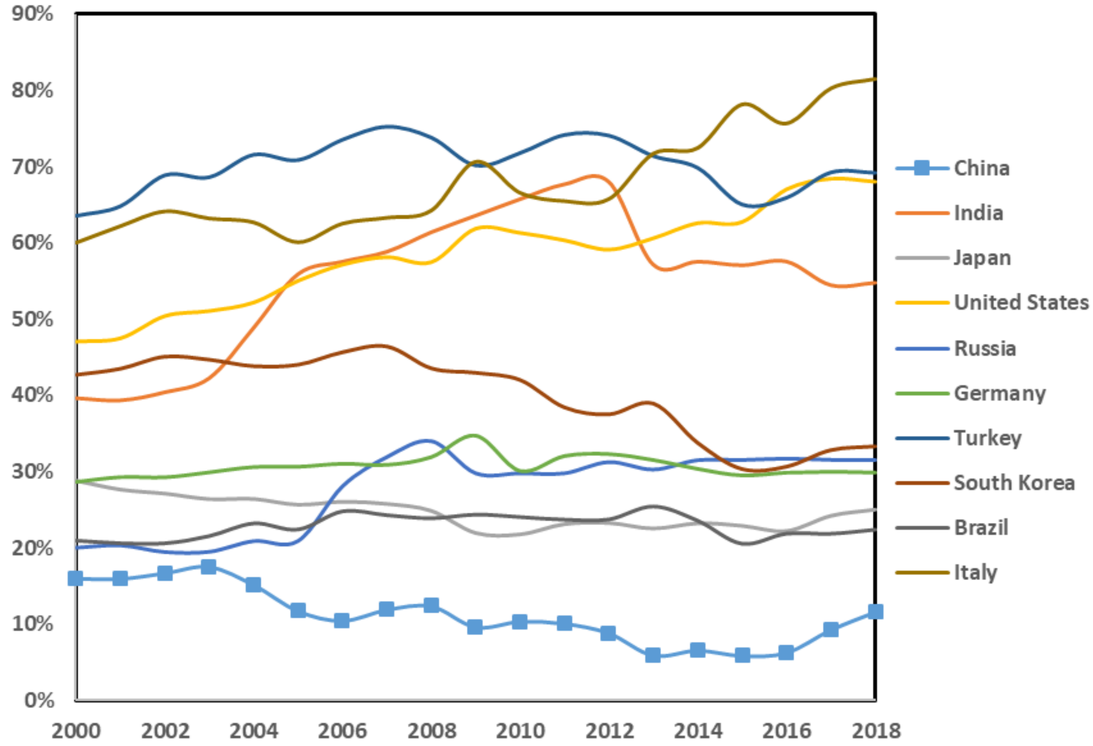


Figure 4. Proportion of short-process steel in the world's top-10 steel producing countries

Although China is unable to rapidly and massively increase its proportion of short-process steel making, and it is difficult to raise the proportion of short-process steel to the level achieved in countries such as Italy and the United States, short-process steel still has great promotion potential and development value in China as described in the following.

(1) Excess capacity and excess inventory risk. China's iron and steel production/consumption has grown rapidly and it is predicted that steel scrap production will also increase rapidly. Additionally, there remain policies such as rapidly increasing consumption on the demand side (such as through accelerating the construction of infrastructure) to solve the problem of excess capacity. These policies will stimulate and promote iron and steel consumption and present the risk of a future surge of steel scrap and iron scrap. Multiple world events like Covid-19 in early 2020 may accelerate the market economic cycle and present the risk of economic contraction, and the global iron and steel industry may see a new round of policy and economic incentives, which will further increase the pressure on steel scrap disposal between 2030 and 2050.

(2) Contraction risk of industrial transfer and international trade. China is often described as the world's factory. However, as domestic production costs rise with future economic development, and countries represented by the United States encourage conservatism and a return of industry to their own shores, there is a risk that the iron and steel industry will shift to less-developed countries and return to developed countries. Additionally, as previously mentioned, various events in early 2020 accelerated international tensions, which is likely to affect international trade in the long run. Short-process steel making might become the steel-making route of choice and the direction of market expansion for China's iron and steel industry.

(3) Emission reduction benefits from clean power. As China rapidly develops its renewable-energy-based power infrastructure, compared with long-process production, short-process production will see more emission reduction benefits from cleaner power. As a result,

short-process production will be an important technology choice for China's iron and steel industry to independently reduce carbon emissions.

Therefore, although increasing the proportion of short-process steel to the level of developed countries in a short period of time is difficult, it is entirely possible and even necessary to develop short-process steel technology, reduce the cost of short-process steel, build a comprehensive utilization system for steel scrap and improve the output of short-process steel in dealing with the potential risks facing the iron and steel industry. In the face of a possible "scrap tide" and "industrial transfer tide" in the future, short-process steelmaking will play an important role in handling steel scrap, ensuring iron ore resources and expanding China's iron and steel industry market. There is thus great potential for the rapid development and carbon emission reduction of the iron and steel industry in China.

1.3 Purpose and arrangement of this report

This report starts with hydrogen-energy metallurgy, an ultra-low emission steelmaking technology, in investigating the technical path, greenhouse gas emissions and energy consumption of China's iron and steel industry in the pursuit of China's goals of a carbon peak and carbon neutrality. The investigation is based on a thorough understanding of the development status and the selection of emission reduction technology for China's iron and steel industry. To this end, this report outlines the present state and development of China's iron and steel industry; anticipates the future market demand for the iron and steel sector based on the literature and historical data; presents an outlook on the emission reduction technology of the iron and steel industry from the three perspectives of management optimization, the improvement of traditional process technology and the development of ultra-low emission technology; combines existing project overviews and life-cycle analysis to analyze the application potential and cost of hydrogen-energy steelmaking technology; analyzes the change trends of the energy consumption and CO_2 emissions of China's iron and steel industry in various future scenarios on the basis of the contents of the first four parts; and presents key conclusions and makes policy recommendations.

2. Steel Demand and Production Demand Analysis

Since the commencement of reforms and the opening up of China in 1978, industrially added value has accounted for 33%–45% of the national gross domestic product (GDP) of China, and industry has contributed more than 40% of economic growth in China. Meanwhile, China has surpassed the United States as the world’s top energy consumer. Carbon emissions are rising in tandem with the acceleration of industrialization and urbanization, as is the demand for energy in the industrial sector. China accounted for 30% of global CO_2 emissions in 2017 and is now the world's greatest emitter of CO_2. The iron and steel industry is known for its high energy consumption and enormous emissions. Coal-based energy has become China’s third-largest source of CO_2 emissions owing to its energy structure In this context, maintaining economic vitality while reducing carbon emissions is critical to the industrial transformation of energy-intensive sectors, such as the iron and steel industry.

Forecasting the future demand for crude steel is thus crucial. Such forecasting is the basis for the predictions of carbon reduction technologies in the iron and steel industry and offers basic indicators required for calculating the carbon reduction cost and green premium of major zero-carbon technologies in China's iron and steel industry.

In this report, we establish basic and low-demand scenarios with which to study the future steel demand till 2060. In the low-demand scenarios, we mainly refer to methods described in the demand chapter of the sixth report of the Intergovernmental Panel on Climate Change for reduction of the steel demand; i.e., the demand is reduced through the avoid, shift and improve strategy.

The “avoid” option includes reducing the demand for transportation services through online meetings, telecommuting, a compact urban layout, reduced commuting and shared transportation; reasonably reducing living areas; and avoiding large-scale demolition and construction.

The “shift” option includes developing public transportation, slow transportation and converted transportation services and creating an expanded centralized living mode.

The “improve” option includes improving material efficiency, reducing the use of materials and making efficient use of materials.

The following sector analysis of the demand for steel reveals that the avoid, shift and improve options mentioned above are available to the automotive, construction and machinery industries, among other commodity manufacturing industries.

In addition, we design indicators for the change from the low-demand scenarios to the basic scenarios by referring to the promotion measures of existing research: (1) the steel demand of the construction industry (reducing by approximately 20% from the basic scenarios to the low-demand scenarios in 2060), with the main measures being compact cities, residential area optimization and design factors; (2) the steel demand for machinery and other industrial production (reducing by 20% from the basic scenarios to the low-demand scenarios in 2060), with the main measures being a longer product life, reuse and recycling, access to resources, more efficient services and more energy-efficient materials; and (3) steel demand for automobile transportation products (reducing by approximately 20% from the basic scenarios to the low-demand scenarios in 2060), with the main measures being online meetings and slow transportation, developing public transportation, sharing and compact cities.

2.1 Overview of research conducted in China and abroad

The domestic and international literature reveals that, for a long time, a major growth pattern of China's economy has been large-scale investment and the establishment of large-scale projects by central and local governments. The steel demand is greatly affected by governmental policies and central decisions.

However, in the same Five-year Plan period, the policy factors affecting steel demand would remain roughly unchanged. As a result, most predictions of the steel demand in China are based on a five-year cycle. Surely, we can also analyze a 10-year scenario in light of China's goals of a carbon peak and carbon neutrality and relevant steel policies.

Joint sequence modeling (see sections 2.1.1 and 2.1.2 for details) and a decomposition method (see section 2.2 for details) were adopted for analysis in this study.

According to predictions made by Chinese enterprises and the China Metallurgical Industry Planning and Research Institute, joint sequence modeling was used as a prediction made using the steel consumption coefficient. The present study forecast China's steel demand using the GDP consumption coefficient and fixed asset investment consumption coefficient on the basis of the change law and characteristics of the relationship between the GDP, fixed asset investment, and steel consumption coefficient. This study makes several contributions to the literature. However, although the study used a wide range of technical data processing methods, it paid less attention to policies and industrial principles, limiting its use in specialized industry research..

The decomposition method is derived from and is evolved into the prediction of downstream industry consumption method of Chinese enterprises and the China Metallurgical Industry Planning and Research Institute. It is widely used in specific industry research owing to its greater consideration of policy and industry fundamentals.

The present study adopted regression analysis, system dynamics modeling, cointegration and grey system theory, wavelet transformation, DGM and a Kalman filtering algorithm for the data analysis and predictions.

2.1.1 GDP-dominated joint sequence modeling

GDP-dominated joint sequence modeling takes the GDP as an important factor for consideration. Most studies divide the GDP into consumption, investment, net exports and government purchases and take other economic or non-economic factors as independent variables in modeling the demand for steel.

As shown in Figure 5, Gao Xinrui et al. from the Research Center for Strategy of Global Mineral Resources at the Chinese Academy of Geological Sciences conducted a cross-sectional analysis of the peak years of steel consumption in the industrialization of typically developed countries using the S-shaped law of the per capita steel consumption and per capita GDP [30]. They considered high-increase, reference and low-increase schemes according to China's economic growth development goals in analyzing China's future steel demand. They concluded that, in the case of the high-growth plan, China's per capita steel consumption peaks in 2015, with per capita steel consumption of 480–500 kg and total consumption of 670–700 Mt. Obviously, these data are not based on reality.

The historical experience and relevant prediction of steel consumption during the industrialization of developed countries [31–33] show that the basic judgment that the per capita steel consumption and per capita GDP (calculated in Geary–Khamis dollars for the year 1990, also known as the 1990 GK US dollars) having an S-shaped trend is indeed basically accurate.

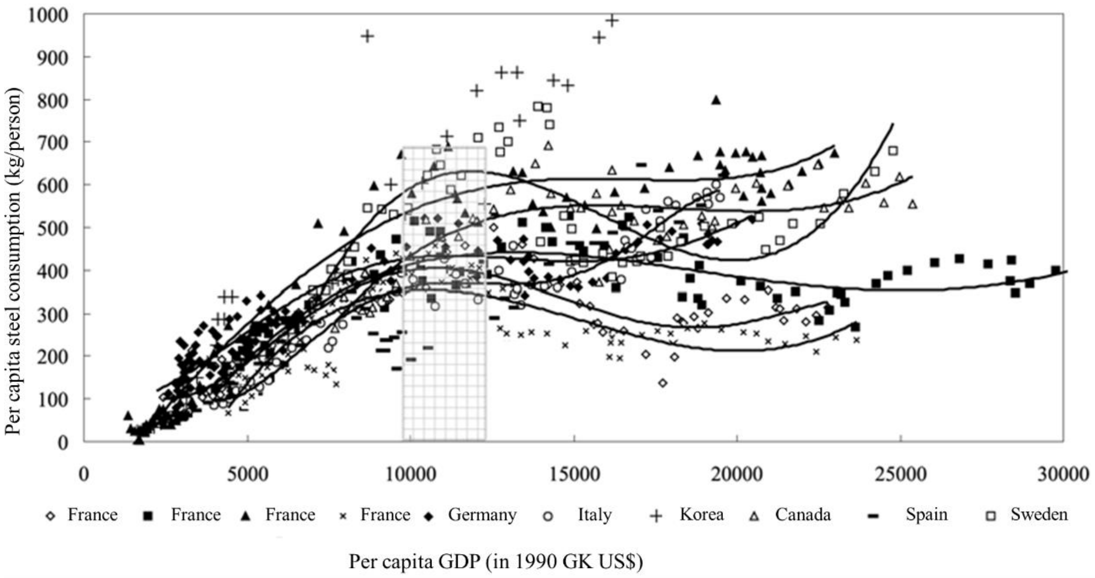


Figure 5 S-shaped law of per capita steel consumption and per capita GDP in typical developed countries

Adopting the basic idea of the model, as shown in Figure 6, we investigated and sorted the relevant parameters and indicators of the apex of the S-shaped law for 10 countries of the Organisation for Economic Co-operation and Development. Thee parameters included the peak value of the per capita steel consumption, per capita steel accumulation, economic structure, urbanization rate, infrastructure and social wealth accumulation level. We concluded that the peak index of per capita steel consumption in China can be used for reference.

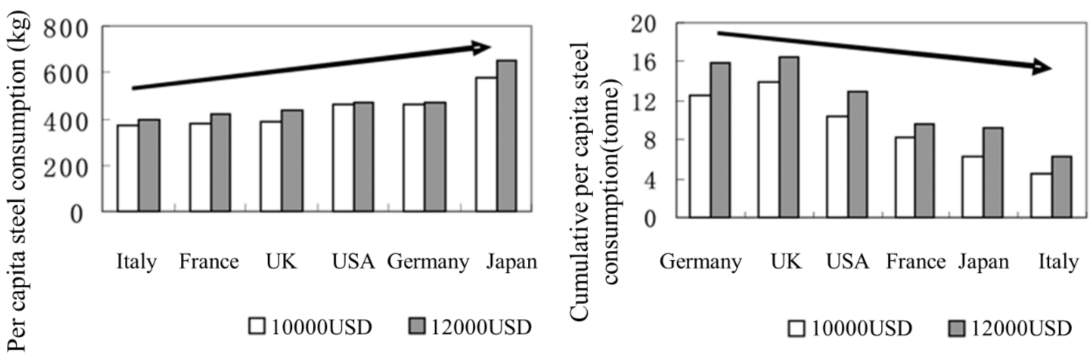


Figure 6 Per capita steel consumption vs. cumulative per capita steel consumption in typical developed countries with per capita GDP of US$10,000–12,000

Gao Chengkang et al., of Northeastern University proposed the H value (i.e., the ratio of total steel to GDP) as an important indictor of steel prediction [34]. The consumption of steel is calculated from the GDP and H value to obtain the steel output, and the steel consumption is finally learned through the relationship between steel consumption and steel output. The results show that the GDP, H value and delta tau affect steel production. Steel output increases with the GDP. Meanwhile, steel output decreased with increases in H and delta tau, but the main influencing factor is the GDP.

The above conclusion was also made by Lin Gu et al. [35], who gave a more accurate crude steel output of between 804 and 841 Mt.

2.1.2 Joint sequence modeling dominated by other factors

The joint sequence modeling dominated by other factors takes non-economic factors as an essential consideration and obtains a lower proportion than the GDP-dominated joint sequence modeling.

The construction of urban infrastructure and the construction of civil dwellings are both steel-cost projects, implying that urbanization will most likely synchronize with growth in the demand for steel. To test this hypothesis, Peng Tao et al. [36] used the urbanization rate as the main influencing factor in building a system dynamics model on the Vensim PLE platform to estimate the peak steel demand in various scenarios defined by varying injection rates. Their results show that, with an urbanization rate of 70% to 75%, China's maximum steel demand reaches 1 billion tonnes per year, on the same level as the demand in developed countries. With excitation, the peak may appear earlier, but its value does not change greatly.

Other Chinese studies [37–41] have concentrated on GDP-dominated joint sequence modeling. There is also joint sequence modeling that is dominated by other factors and intersects with GDP-dominated modeling, but it is not part of mainstream theory. Nonetheless, there are studies [42] that support such modeling.

2.2 Decomposition modeling

2.2.1 Prediction and analysis of the China Metallurgical Industry Planning and Research Institute

The China Metallurgical Industry Planning and Research Institute [43] reported that they expect the output of crude steel to continue to decline in 2022.

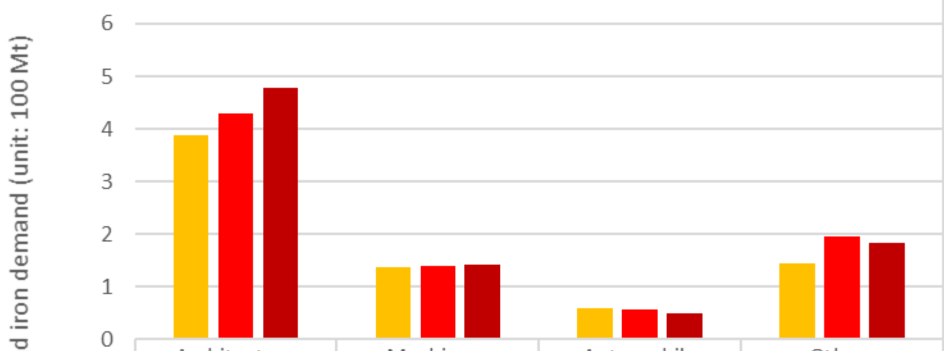
The present study used the steel consumption coefficient method and downstream industry consumption method to comprehensively predict China's steel demand in 2021 and 2022. In light that different methods have different characteristics and limitations, the results of these two methods were weighted. It is estimated that China's steel consumption in 2021 will reach 954 Mt, marking a year-on-year decrease of 4.7%, whereas China's steel demand in 2022 is expected to be 947 Mt, marking a year-on-year decrease of 0.7%.

On December 15, 2021, the China Metallurgical Industry Planning and Research Institute released a report predicting that in 2021 and 2022, China's crude steel output would be 1.040 and 1.017 billion tonnes respectively, marking year-on-year decreases of 2.3% and 2.2% respectively. Correspondingly, the crude iron output and iron ore import would decline. Hence, the prohibition of new production capacity will still be a bottom line in 2022, and the overall supply and demand of steel will decline steadily.

Annual data can also be obtained from China's steel series reports (blue books) issued by the China Metallurgical Industry Planning and Research Institute.

2.2.2 Prediction of downstream consumption by industry

Most reports present only conclusions without detailed sub-industry modeling and analysis, and we thus briefly studied the prediction results using a decomposition method. As 2021 has only just passed and there are no basic statistical data for this year, and because China's economy was greatly affected by the COVID-19 pandemic in 2020, we disregarded data for these to years and analyzed only data for the period of the 13th Five-Year Plan, which finished in 2019 (Figure 7).



	Architecture	Machinery	Automobile	Others
2017	3.87	1.36	0.58	1.45
2018	4.3	1.4	0.56	1.95
2019	4.78	1.42	0.5	1.84

Figure 7 Steel and iron demand of major downstream industries in 2017–2019

The downstream demand for steel and iron mainly comes from construction (including real estate and infrastructure) and the manufacture of machinery and automobiles. According to the calculation of the steel stock structure [43] issued by the China Metallurgical Industry Planning and Research Institute in 2019, the steel demand structure of downstream industries changed slightly in 2019. Specifically, in 2019, the consumption of steel in the construction industry reached 478 Mt, marking a year-on-year increase of 11.2% and accounting for 54.1% of the total; the consumption of steel in the machinery industry reached 142 Mt, marking a year-on-year increase of 1.4% and accounting for 16.1% of the total; the consumption of steel in the automobile industry fell to 50 Mt, marking a year-on-year decrease of 10.7% and accounting for 5.7% of the total; the consumption of steel in the energy industry reached 34 Mt, marking a year-on-year increase of 3.0% and accounting for 3.9% of the total; and the consumption of steel in the shipbuilding, household appliance, railway and container industries respectively changed by −8.3%, 7.7%, 0.0% and −16.7% respectively year-on-year, accounting for 1.2%, 1.6%, 0.6% and 0.6% of the total.

We thus used data for the period from 2017 to 2019 in the analysis.

(1). Construction industry

Many real-estate regulation policies were released in China in 2021. Figure 8 shows that, according to incomplete statistics, governments at all levels released 521 real estate regulation policies in 2021, an average of 1.5 regulation policies per day, demonstrating that real estate is one of the industries most of concern to the government.

We cannot simply use data on EPS for regression calculation because of the reduced leverage of the real estate industry.

In terms of the macroscale economy, China's economy is expected to continue to recover steadily in 2022. However, China's economy will continue to face new challenges and downward pressure because of increasingly unstable and uncertain factors in the domestic and international environments. Without relaxing the supervision of real estate finance, monetary policies may continue to stabilize the economy, increase support for the "six stabilities" and "six guarantees", and maintain stable growth in the total quantity of money and credit, and management of real estate finance may be further improved.

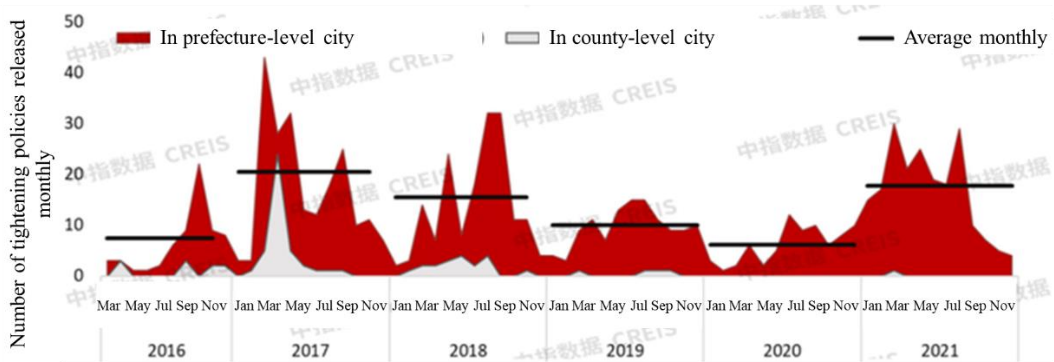


Figure 8 Number of real estate tightening policies issued by key cities since 2016

(Data source: The material was comprehensively sorted by the China Index Academy.)

The central government will maintain its general tone of "housing for non-speculation" to meet the 2022 goal of the "three stabilities." As the adjustment trend of the real estate market deepens, the credit environment is projected to improve more notably, and the general trend is expected to continue through the first quarter of 2022. The credit end, meanwhile, is less likely to be considerably eased under the monitoring of the "two red lines" at the bank end. A pilot real-estate tax program may be implemented, with a list of pilot cities and collection rules expected to be released soon, which could affect the expectations of house buyers in the near future.

The "medium and long-term development dynamic model of China's real estate industry" analysis reveals that the real estate market is mainly affected by external factors, such as economic growth, the improvement of money and credit and real-estate regulation policies (Table 1).

Table 1 Forecast of various indicators of China's real estate market in 2022

(Data source: Prediction and calculation by the China Index Academy)

Index	Sales area of commercial housing (100 million m^2)	Sales price of commercial housing (yuan / m^2)	Investment in real estate development (trillion yuan)	Construction starts (100 million m^2)
Absolute quantity	16.1–16.4	10,402–10,550	15.2–15.4	19.1–19.4
Year-on-year increase	−8.3%–−6.8%	2.0%–3.5%	1.5%–3.0%	−5.5%–−4.0%

We therefore infer that **the basic steel consumption of the construction industry in 2022 will be 430 Mt** from the ratio of the construction starts in 2022 to that in 2017–2019 (Table 2).

Table 2 Regression prediction of construction starts and steel demand in China

Year	Construction starts (10,000 m^2)	Steel demand (100 Mt)
Predicted maximum in 2022	194,000	4.4611
Predicted minimum in 2022	191,000	4.4011
2019	227,162.78	4.78
2018	209,537.16	4.3
2017	178,653.77	3.87

As the real estate market is affected by the macroscale economy, although China's real estate industry, which is booming as a whole, has a slow growth rate. With reference that there is an inflection point of construction starts for both European and American countries, we found that China's construction starts peaked in 2019 as shown in Table 3. We therefore fitted the construction starts in China through the inflection point and its subsequent data. We then obtained the steel demand of the construction industry through the regression prediction between the construction starts and steel demand. The Chinese Academy of Social Sciences expects that in the period of the 14th Five-year Plan, there will be a turning point in the trend of the area of new housing; i.e., the absolute volume of housing sales will begin to decline. According to the trend predicted by the Chinese Academy of Social Sciences, the new housing area will decline slowly from the inflection point. As only a gradual and stable increase in the production capacity can ensure the long-term and stable operation of China's real estate market, we applied logarithmic fitting.

Table 3 Statistics of construction starts in China

Year	Construction starts (10,000 m^2)
2016	166,928
2017	178,653
2018	209,537
2019	227,163
2020	224,433
2021	198,895
Predicted average in 2022	192,500

Furthermore, considering that the volume of construction starts will decrease by approximately 20% in the low-demand scenarios, we make predictions for standard scenarios and low-demand scenarios, as shown in Figure 9.

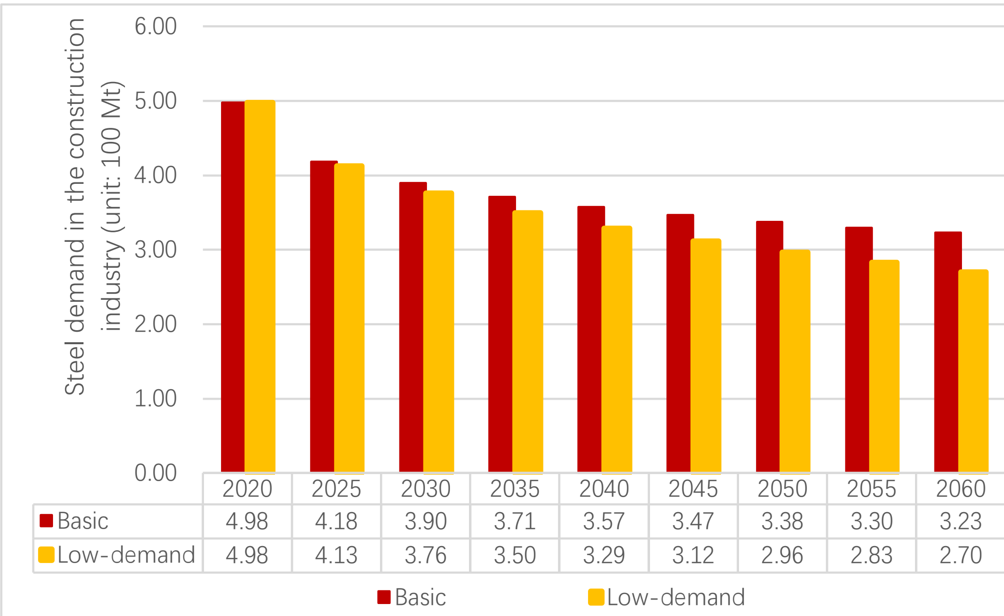


Figure 9 Forecast of the demand for steel in the construction industry

(2). Machinery industry

After an in-depth market adjustment from 2011 to 2015, the construction machinery industry has benefited from China's increased investment in infrastructure construction and grown for four consecutive years since 2016. The operating revenue of the whole industry reached 500 billion yuan in 2017 and soared to a record high of 668.1 billion yuan in 2019, marking a year-on-year increase of 12%. The operating revenue of China's machinery industry in 2021 was expected to reach 779.22 billion yuan by the China Commerce Industry Research Institute.

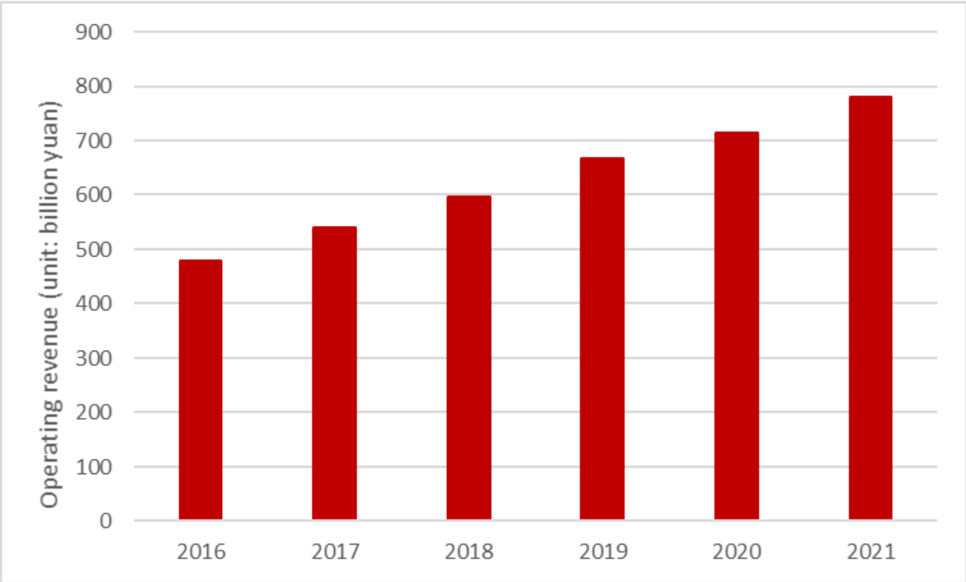


Figure 10. Operating revenue statistics of China's machinery industry

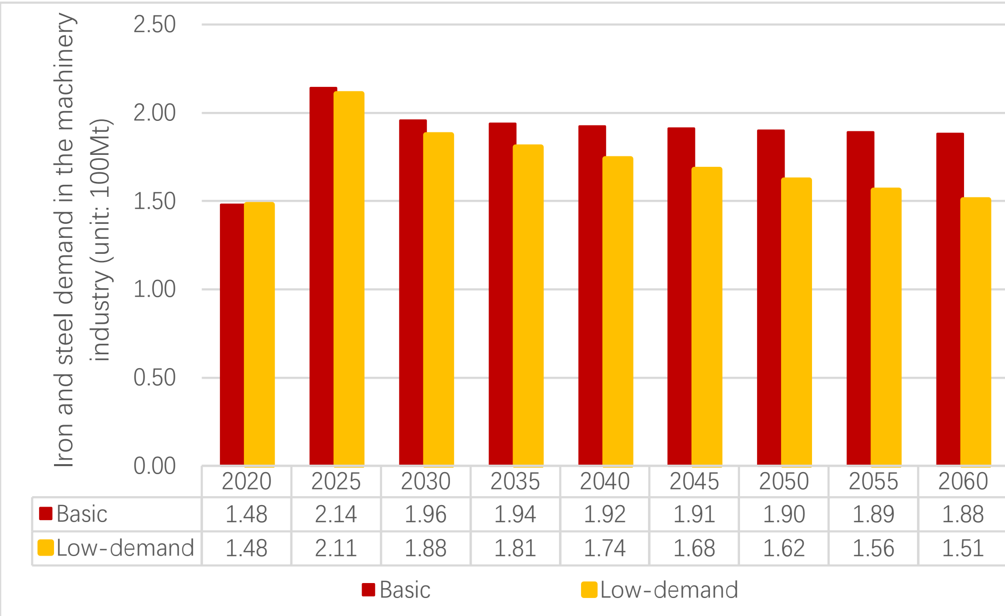
(Data source: China Commerce Industry Research Institute)

We first predicted the operating revenue of the machinery industry. The iron and steel demand was then predicted using the ratio of the unit revenue to steel demand.

For the prediction of the most important operating revenue, we judged from the current statistical results of the operating revenue of China's machinery industry (Figure 10) that the operating revenue of China's machinery industry has had a period of linear stable growth in recent years. Meanwhile, considering the strategic goal referred to as Made in China 2025, we conclude that the operating revenue of China's machinery industry will peak around 2025. Afterward, like that of the construction industry, the operating revenue of the machinery industry will decrease slowly and gradually enter a stable and orderly market state after an inflection point. Additionally, we analyzed the data before 2025 through linear fitting and data after 2025 through logarithmic fitting.

As the fundamental material used in the construction industry, steel plays an irreplaceable role and its use per unit building area cannot be reduced through technological progress or extensive innovative designs. However, the situation is different in the machinery industry as advances in material technology and machine tool structures can gradually displace the use of some iron and steel.

We therefore need to consider also the low-demand scenario; i.e., the scenario of a reduction in the steel demand of 20% under the unit operating revenue cost of the machinery industry. We thus predict the iron and steel demand of the machinery industry as shown in Figure 11.



	2020	2025	2030	2035	2040	2045	2050	2055	2060
Basic	1.48	2.14	1.96	1.94	1.92	1.91	1.90	1.89	1.88
Low-demand	1.48	2.11	1.88	1.81	1.74	1.68	1.62	1.56	1.51

Figure 11. Predicted iron and steel demand in the machinery industry

(3). Automobile industry

A shortage of chips restricted automobile output and sales and affected the steel demand of the automobile industry in 2021 as shown in Figure 12. In 2022, the automobile industry may still be affected by the shortage of chips in the first quarter; however, later in the year, this situation may be effectively alleviated and the annual automobile output and sales will increase.

Following the construction and machinery industries, the automobile industry is the third-largest consumer of steel, accounting for 6% of the total steel demand in China. The automobile manufacturing industry requires various types of steel, such as sheet steel, high-quality steel, profile steel, strip steel and steel pipes, among which sheet steel and high-quality steel are in greatest demand. Steel for new-energy vehicles, as an important incremental market, has become the focus of competition of iron and steel enterprises. Well-known domestic and overseas steel enterprises have strengthened their layout in this respect.

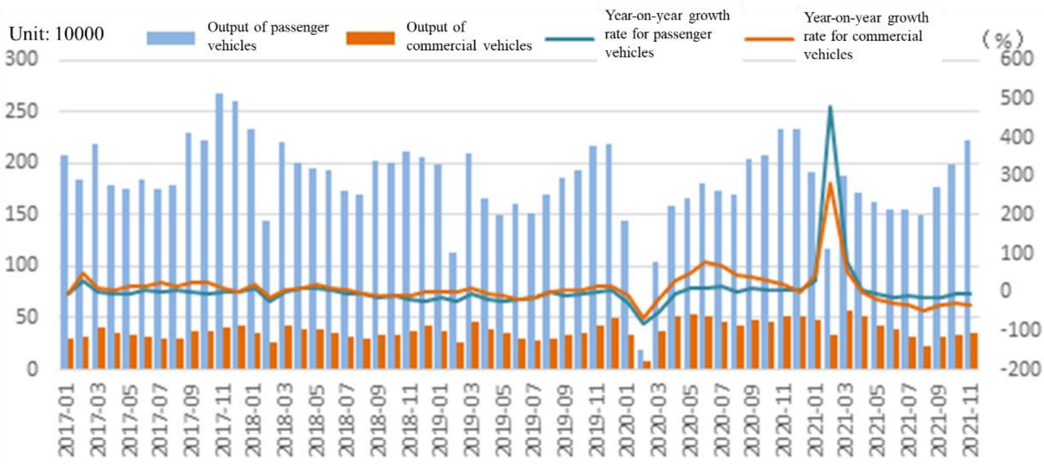


Figure 12. Monthly output and year-on-year growth rate of passenger vehicles and commercial vehicles in China from 2017 to 2021

(Data source: National Bureau of Statistics)

The automobile industry features inconsistent growth rates of the passenger vehicle market and commercial vehicle market, and we thus need to predict sales separately for the two markets.

In the case of the commercial vehicle market in 2022, both the China Association of Automobile Manufacturers and the China Automobile Strategic Development Research Center of Tianjin University predicted that the sales of commercial vehicles would fall below sales in 2021 as shown in Figure 13. However, like China's stably increasing economic aggregate, commercial vehicle sales will have steady growth momentum in the long run. We therefore analyzed the commercial vehicle market through linear fitting to ensure a sustainable growth rate.

In the passenger vehicle market, sales will pick up steadily after a three-year decline in output and the impact of the pandemic. However, sales will continue to decline steadily and enter a stable state after 2022. We therefore used 23 million vehicles, an average value estimated by all parties, as the benchmark to analyze the data for 2022 and used the data before 2021 excluding the impact of 2022 to analyze the data of 2022 to 2060 through logarithmic fitting.

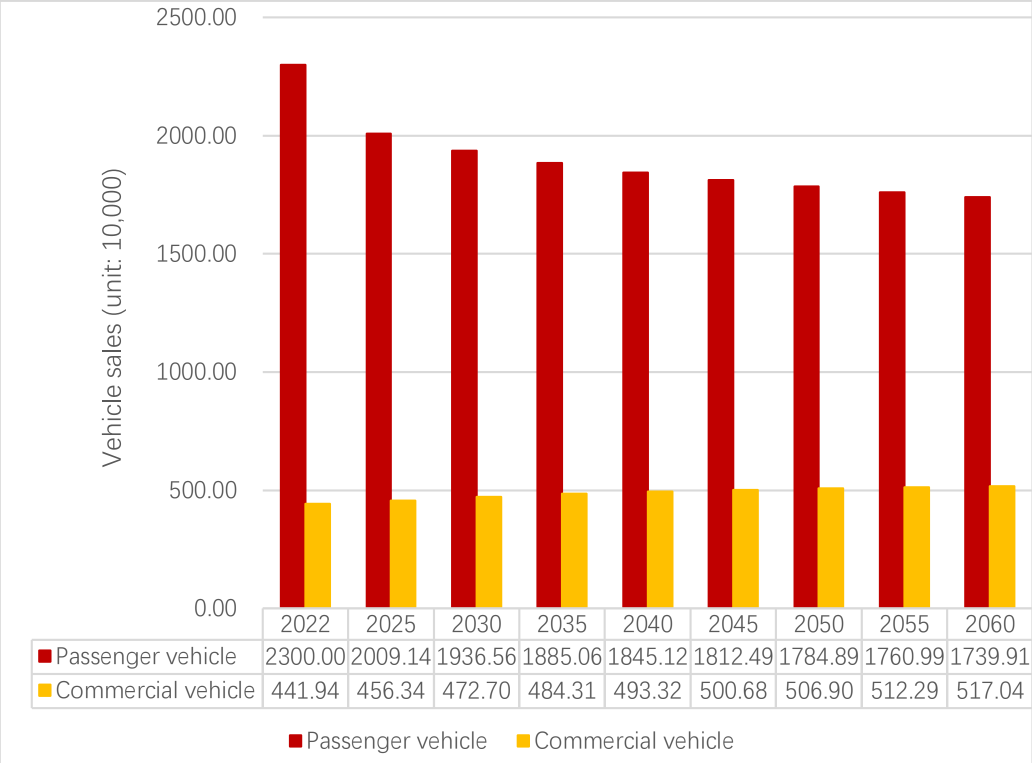


Figure 13. Prediction of sales in China's automobile industry

Like the steel demand in the machinery industry, the steel demand in the automobile industry per unit production decreases with technological progress in the low-demand scenario. Such a phenomenon is mainly seen for the aluminum alloying of automobile parts and even the promotion of an all-aluminum body. We therefore considered the scenario of a 20% decrease in vehicle sales and a 10% decrease in steel consumption per unit sales, as shown in Figure 14.

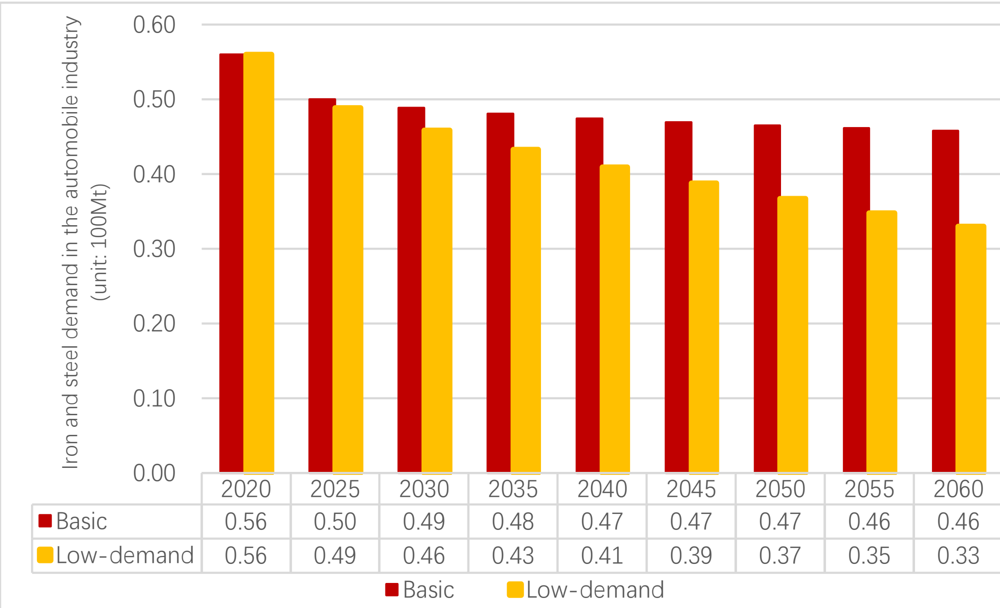


Figure 14. Prediction of the iron and steel demand in the automobile industry

(4). Other industries

Figure 15 shows that other industries account for a small proportion of the iron and steel demand. Major securities companies and fund research departments have predicted that the energy, shipbuilding, railway, household appliances and container industries will have positive and negative scale growth rates in 2022. We thus took the average value of the predicted demand for iron and steel in other industries in 2022 and thus inferred that the total iron and steel demand in other industries is approximately 277 Mt.

Considering that the demand for iron and steel in other industries, especially the energy, shipbuilding, railway and container industries, remained largely stable, we can regard 277 Mt as a stable value of the iron and steel demand in other industries in the long-term prediction. So it is predicted that the demand for steel in other industries will reach 277 Mt in 2030 and 277 Mt in 2060; i.e., it will be basically unchanged.

In view of China's goals of a carbon peak and carbon neutrality, we still considered the effect on the steel demand in the low-demand scenario; i.e., when there is a 20% decline in output.

2.3 Predictions

By summing the results presented in section 2.2, we conclude that China's iron and steel demand will reach 975 Mt in 2022, which is 28 Mt greater than 947 Mt, China's steel demand in 2022 as predicted by the China Metallurgical Industry Planning and Research Institute, which is a small difference. By 2060, China's demand for iron and steel will reach approximately 834 Mt in the basic scenario and approximately 675 Mt in the low-demand scenario.

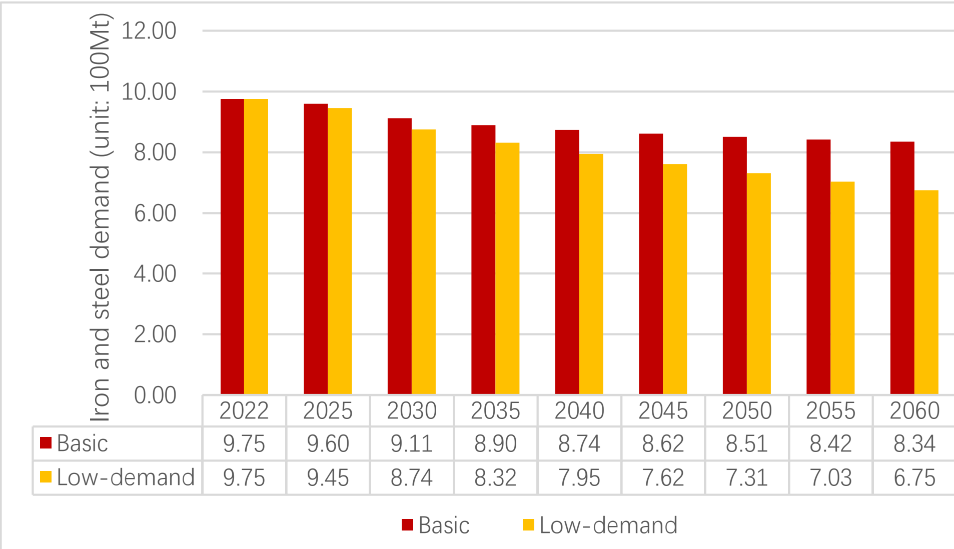


Figure 15. Prediction of China's iron and steel demand

2.4 Comparison with the results of similar research

We made comparisons with the results of similar research for the period from 2010 to 2050 [11, 44–65]. Because of differences in the research period, we could not compare data for the period after 2050, as shown in Figure 16.

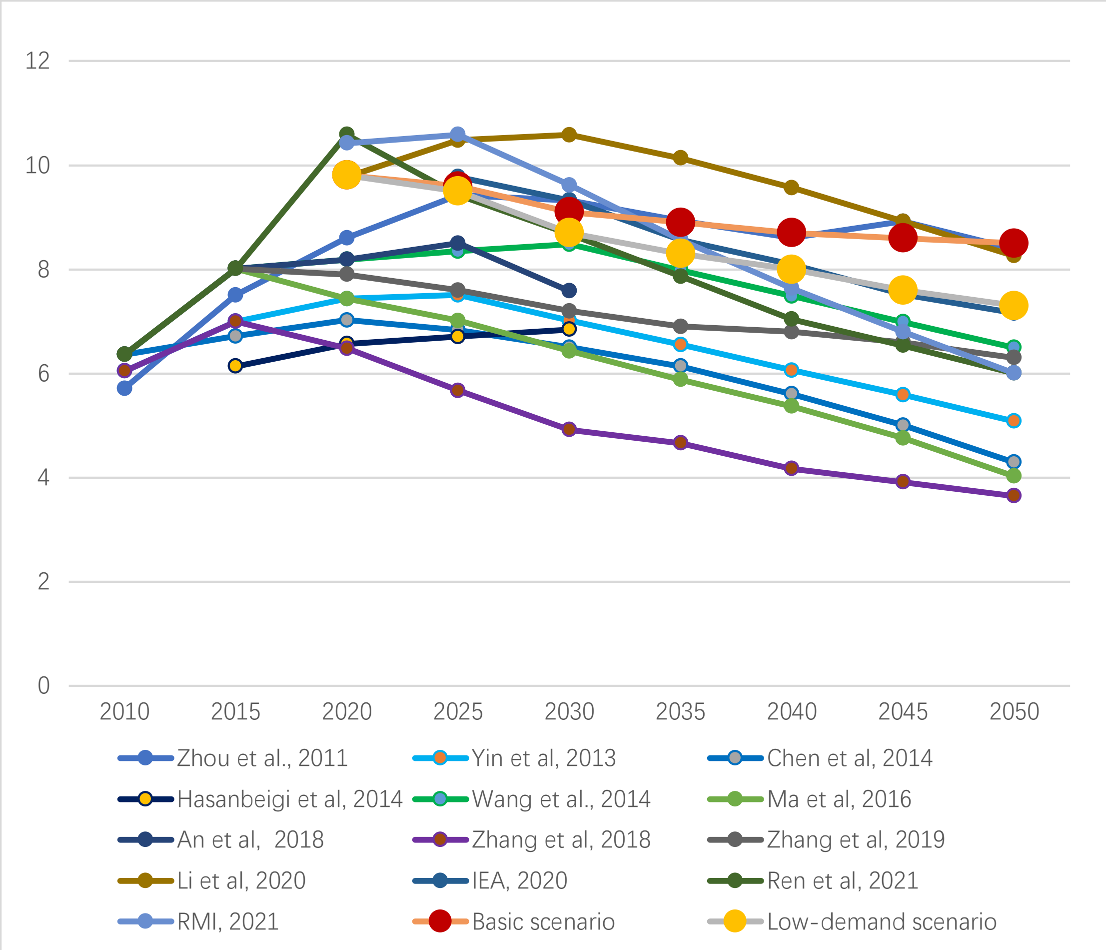


Figure 16. Comparison of predictions of China's iron and steel demand

We conclude that our prediction results are reasonable in that they overlap the results of other studies for both the basic scenario and low-demand prediction scenario.

3. Prospects of Iron and Steel Production Technology

As mentioned in section 1.2, there are three main methods of reducing the emissions of greenhouse gases in the iron and steel industry. The first method is to optimize from the consumption end and the production end by various management means. In the case of the consumption end, the focus is on reducing the steel waste and demand, whereas in the case of the production end, the focus is on improving the energy and material efficiency. The second method is to spread the use of low-carbon technology and to improve the current mainstream BF-BOF and scrap-EAF processes. The third method is to develop and spread the ultra-low emission steel making technology represented by hydrogen metallurgy and carbon capture, utilization and storage. This section discusses these three aspects of the prospects of steel production technology.

3.1 Management optimization

3.1.1 Consumption end

Energy consumption and emissions can be reduced at the consumption end of the iron and steel industry by improving the use efficiency of iron and steel products, slowing the growth rate of the steel demand and enhancing the use efficiency and service life of iron and steel products as follows.

Revision of the design to save steel. In the construction field, the steel consumption of commercial buildings in developed countries is twice the basic required consumption of the safety standards at present, but the service life of buildings has not been improved and most buildings will be demolished and rebuilt within 30 to 60 years. In other words, if the building design is improved according to safety standards and the replacement cycle is extended, the relevant steel demand and consumption are expected to decrease by half or more [66, 67]. **In the transportation field,** it is important to have lightweight vehicles. That is to say, the production and use of more small and lightweight vehicles without reducing the level of supply and service can decrease the iron and steel demand exponentially. Generally, finite element analysis has been adopted for the body design to achieve structural optimization and decrease the steel consumption on the premise of ensuring the physical characteristics of parts [68]. **In the industrial field,** the service life and work efficiency of the production line itself and industrial products involving iron and steel can be improved to reduce the loss of iron and steel.

Material substitution. Relatively clean materials can be substituted for iron and steel materials to reduce the use of iron and steel, such as by introducing aluminum alloy and carbon fiber into production in the automobile industry. For example, in the transportation industry, the China Society of Automotive Engineers issued China's first "Energy-saving and New Energy Vehicle Technical Roadmap" in October 2016 [69]. The roadmap describes the development blueprint of China's automobile industry technology in the next 15 years, with low-weight designs becoming an important element of energy-saving and new-energy vehicles. The roadmap puts forward medium and long-term development plans of lightweight vehicles and development goals for 2020, 2025 and 2030 clearly. Table 4 shows that the lightweight materials of aluminum alloy, magnesium alloy, carbon fiber and other substitute materials are important directions of development.

Table 4. Development roadmap of China's automobile lightweight material technology

Year	2020	2025	2030
Curb weight	10% lighter than in 2015	20% lighter than in 2015	35% lighter than in 2015
High-strength steel	The use of AHSS steel with strength exceeding 600 MPa reaches 50%	Third-generation automobile steel is used at 30% of the white body weight	Steel with strength exceeding 2000 MPa is used at a certain ratio
Aluminum alloy	Aluminum alloy for a single vehicle reaches 190 kg	Aluminum alloy for a single vehicle reaches 250 kg	Aluminum alloy for a single vehicle reaches 350 kg
Magnesium alloy	Magnesium alloy for a single vehicle reaches 15 kg	Magnesium alloy for a single vehicle reaches 25 kg	Magnesium alloy for a single vehicle reaches 45 kg
Carbon fiber reinforced composite	Carbon fiber is used to a certain extent, and the cost is 50% lower than that in 2015	Carbon fiber used accounts for 2% of the body weight, and the cost is 50% lower than that in the last stage	Carbon fiber used accounts for 5% of the body weight, and the cost is 50% lower than that in the last stage

Steel recovery and reuse. In 2019, the annual steel scrap resource in China reached 241 Mt. Various academic studies have predicted that China's steel scrap resources will increase to 280–430 Mt by 2030 and to 490–600 Mt by 2050 [11, 50, 70–72]. However, the total treatment capacity of the steel scrap treatment enterprises licensed by the Chinese government has only reached approximately 100 Mt at present [72]. A well-structured recovery, recycling and reuse system should thus be established in the iron and steel industry and additional policy support should be given to the recovery industry to promote the technological development of the EAF. According the results of our life-cycle analysis (see section 4.2), if all iron scrap and steel scrap is recovered, an additional greenhouse gas emission reduction of 60–110 Mt by 2030 and 130–170 Mt by 2060 will be realized in the iron making process. At the same time, the ratio of EAF steel making can increase to 40% to 70%, which will greatly improve the electrification rate of the iron and steel industry and strengthen the application of renewable energy.

3.1.2. Production end

Management technology at the production end has the potential to realize energy savings and reduce emissions by optimizing the production process. Industrial reform can be enhanced using information technology, the intelligence of the steel-making industry becomes an important technical choice to further improve efficiency at the management level, and by intelligent means, iron and steel enterprises have the chance to realize efficient, continuous and stable production, reduce material and energy consumption in the steel-making production process and finally reduce CO_2 emissions [73]. Information-technology-based advanced management methods have been applied to the whole process of the iron and steel industry, including BOF, EAF, casting and workshop operations. Specifically speaking, these methods focus on the control over the reaction end and the static control model, furnace gas analysis and control system, and sonar slagging technology applied in the BOF process. In the EAF process, this technology aims to improve the automatic charging of steel scrap, intelligent power supply and digital electrode control technology. In casting, management technology mainly focuses on quality control and efficiency improvement, including the use of a multi-functional casting platform robot, ladle slag detection system, energy-saving flameout billet cutting and other advanced technologies. Finally, the methods of managing the workshop operation process include label tracking, hot-metal temperature control/distribution and the use of intelligent casting cranes [74]. The methods can be categorized as those of enterprise resource planning, production process detection and control, automatic material processing and energy system optimization [23]. The first three types reduce the material/energy consumption of steel making to the theoretical value, and the optimization of energy system can reduce energy consumption in the BF-BOF process by 1% to 3% [6, 75, 76].

In summary, China's iron and steel industry has experienced a shift from experience-based management to modern management. The energy saving/material saving management project has become a part of the whole enterprise management strategy but not the responsibility of a single sector. Additionally, the real-time, intelligent and effective human–computer interaction management system and the collaborative management of material/energy flow have room for further improvement.

3.2 Improvement of traditional process technology

Many measures can be taken to improve various process links in long-process/short-process steel making [19, 77–81]: (1) improving gas circulation, products and waste flow; (2) enhancing the feeding process by feeding powdered coal; (3) optimizing the steel-making furnace design and process control; (4) reducing the number of temperature cycles adopting dry quenching, a top-pressure turbine device, thin-strip continuous casting production and other optimized processes; and (5) recovering and reusing the residual gas, waste heat and waste materials in all links. In fact, the iron and steel industry itself has had a strong sense of technological development and undergone several technological iterations with the expanding iron and steel market. In the more than 30 years that have passed since 1980, and especially in the 1980s and 1990s, China's iron and steel industry completed key technology iterations, such as the BOF replacing the open hearth furnace, continuous casting replacing mold casting and the rolling-in-one-heat process replacing the rolling-in-multiple-heat process. These changes have had provided fruitful results and thus gradually decreased the marginal benefit of improvements in BF-BOF technology. It appears difficult and costly to make energy savings of another 20% through technical improvements [82]. In the face of the need for low-carbon development in the iron and steel industry, we should carry out cost/benefit analyses of the new technology options to clarify the development focus.

3.3 Research and design and demonstration of ultra-low emission technology

The iron and steel industry is regarded as an industry facing difficulty in reducing its carbon emissions because its main process, the irreplaceable BF-BOF process, requires a high temperature and needs coke to play multiple roles in the BF [83, 84]. In addition, optimized management and the technical improvement of traditional processes play limited roles in reducing emissions, and attention has inevitably turned to hydrogen-based DRI-EAF and CCUS, two ultra-low emission technologies with great development potential. This section summarizes the technical features and representative projects of the two technologies.

3.3.1 Hydrogen metallurgy

Hydrogen-energy steel-making technology, in short, substitutes hydrogen for the reducer used in reducing iron ore to pig iron on the traditional steel-making technology route and finds a substitute for coke and other fossil fuels. The core principle is that iron ore reacts with hydrogen to produce sponge iron and water. Hydrogen-energy steel making can solve the problem of CO_2 emissions fundamentally, and it has thus become one of the best-known emission reduction technologies in the iron and steel industry. Countries around world have carried out demonstration projects of hydrogen-energy steel making in combination with their own resource and technological advantages; e.g., ULCOS (European Union [85–90]), HYBRIT (Sweden [91–95]), SALCOS (Germany [96, 97]), COURSE50 (Japan [98–101]) and H2FUTURE (Austria [100]). All these projects have lasted longer than 3 years and some are ongoing and involve large-scale empirical research. Additionally, the Chinese government and Chinese enterprises are interested in hydrogen-energy steel making. In 2019, the Baowu Group began cooperation with the China National Nuclear Corporation and Tsinghua University in hydrogen-energy steel making. Furthermore, the Baowu Group will begin working with the Rio Tinto Group in low-carbon metallurgical innovation.

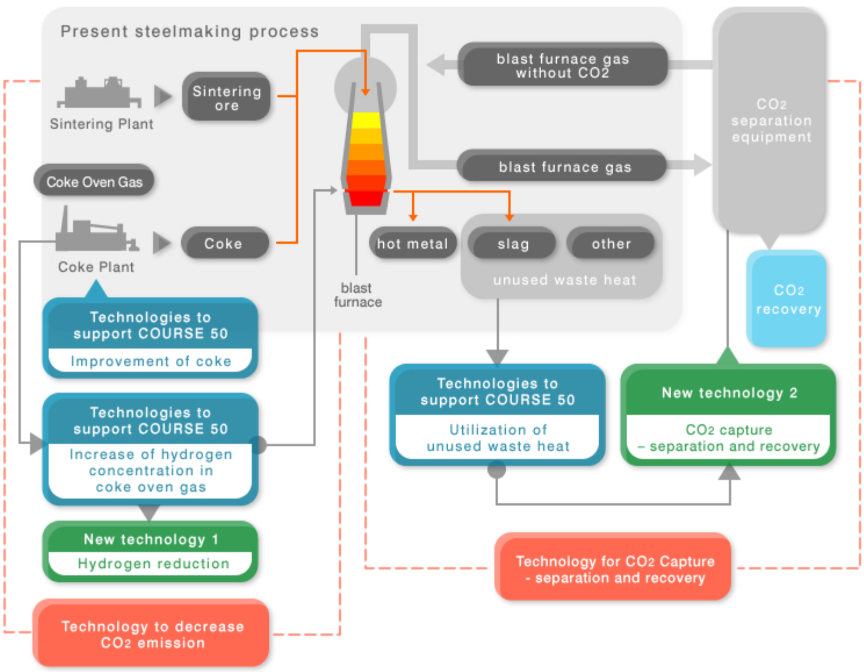
The reduction of carbon emissions achieved using hydrogen-energy steel-making equipment depends on the steel-making technology and hydrogen-production technology used. There are four aspects to steel-making technology.

- Hydrogen technology: The hydrogen content in syngas is improved by upgrading the coke oven gas to reduce hydrogen used in the BF.
- DRI production processes: Practical operation requires the development of technology for blowing hydrogen, technology for optimizing the chemical reaction in the furnace, technology for reducing ore that is hard to reduce and of low grade, quality design technology for coke/sintering ore/slag. The gas-reducer shaft furnace is the most important mode of DRI production; the main suppliers are MIDREX and Energiron HYL [102, 103].
- Development of super heat-resistant/super corrosion-resistant raw materials: It is necessary to first develop storable high-temperature and high-pressure hydrogen and super-corrosion-resistant high-temperature materials at a high temperature exceeding 900 degrees Celsius.

- DRI transportation and treatment system: Produced in a reducing atmosphere, DRI has a sponge structure containing many voids, and it is thus readily broken or oxidized. The frequently cited DRI damage caused by removal is estimated to result in a loss of 0.25% per 2 m of lifting. Removal using ordinary equipment may cause a damage loss of 2.5% through a single transfer point. Considering the oxidation of DRI, there may be a loss of 5% to 8% in the DRI treatment system [102–106]. Closed, insulated and reducing-atmosphere transportation technologies, such as the tubular belt conveyor and pneumatic transportation, should thus be adopted. Additionally, there are other technical options, such as DRI hot feeding and charging and compressed DRI..

Besides the steel making technology itself, the hydrogen source used in hydrogen-energy steel making greatly affects the reduction in carbon emissions. Currently, two main hydrogen sources are used in demonstration projects.

- Gray hydrogen/blue hydrogen (hydrogen from natural gas/by-product hydrogen from the coking industry) + CCUS technology: Such technology is used in the COURSE50 project, whose technical route is shown in Figure 17. The hydrogen separated from coke oven gas is used as the reducer, and the carbon emission reduction effect depends on the performance of the CCUS technology [98].



Source: https://www.jisf.or.jp/course50/outline/index_en.html

Figure 17. **Technical roadmap of COURSE 50**

- Green hydrogen (hydrogen produced from wind/photovoltaic energy, hydrogen produced from waste-heat power generation in steel-making and hydrogen produced from nuclear power): As shown in Figure 18, most demonstration projects plan to eliminate CCUS technology and directly use green hydrogen for production. The HYBRIT, SALCOS and H2FUTURE projects were jointly developed by local iron and steel enterprises, power enterprises and electrolyzer supply enterprises (e.g., Siemens and Sunfire), and hydrogen supply projects (e.g., the sub-project GrInHy2.0 of SALCOS) were established to ensure a supporting supply of wind and photovoltaic renewable energy via electrolyzers. Among the projects, the SALCOS project plans to use waste heat of the iron and steel industry to generate power/supply heat to solid oxide fuel cells besides using wind and photovoltaic energy[95, 96, 107]. Additionally, the Baowu Group has cooperated with China National Nuclear Corporation and Tsinghua University to conduct prospective research on nuclear steel making and nuclear hydrogen production and plans to carry out I-S cycle hydrogen production and power generation using high-temperature gas-cooled reactors and use hydrogen for direct-reduction iron making and power for EAF steel making.

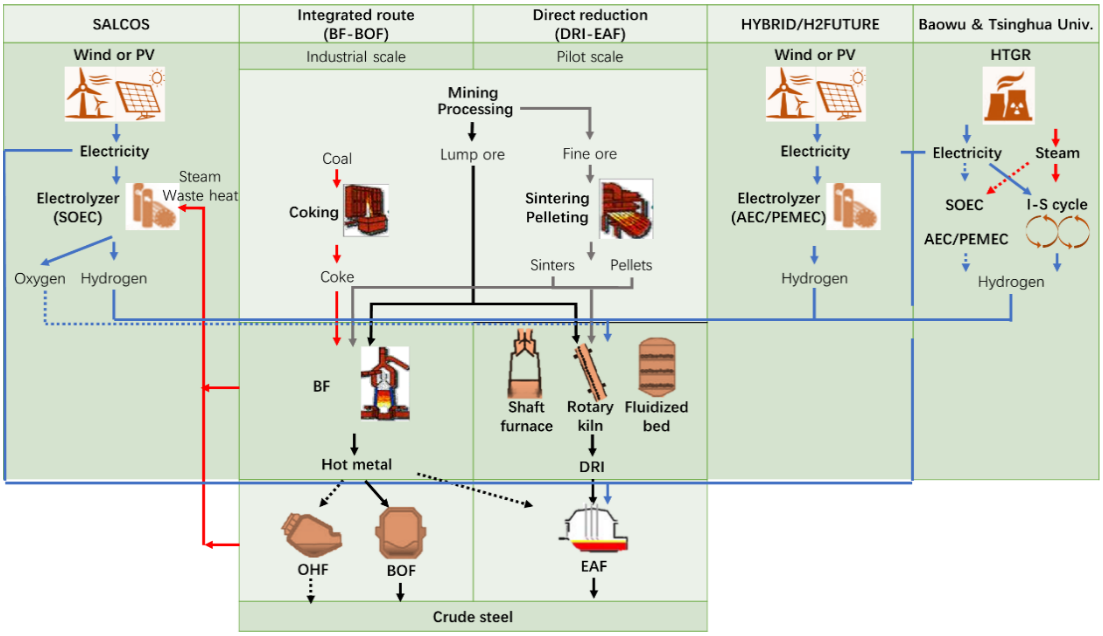


Figure 18. Schematic diagram of green-hydrogen steel-making demonstration projects

3.3.2 CCUS

Before the advent of ironmaking technology that features the direct reduction of clean hydrogen as an alternative, CCUS was largely the only technical option for achieving zero carbon emissions in the iron and steel industry as it was difficult for this industry to eliminate the direct use of fossil fuels such as coal and coke. Meanwhile, realizing zero-carbon emissions in the traditional iron and steel industry has low priority and CCUS technology used in the iron and steel industry cannot improve production efficiency like CCUS technology used in oil and gas extraction. Therefore, compared with technology that aims to improve the efficiency of the iron and steel process, CCUS technology in the iron and steel industry has developed more slowly. The technology selection and classification of each stage of the CCUS process is shown in Fig. 19 [108, 109]. The key step of CCUS is carbon capture, which can be divided into pre-combustion capture (decarbonization of feedstock and fuels), post-combustion capture (exhaust treatment) and oxygen-enriched combustion (where a high concentration of oxygen substitutes for air in combustion to increase the CO_2 concentration in the exhaust and improve the capture efficiency). In China, iron and steel companies are considered to be sources of moderate-concentration CO_2 suitable for pre-combustion and post-combustion capture.

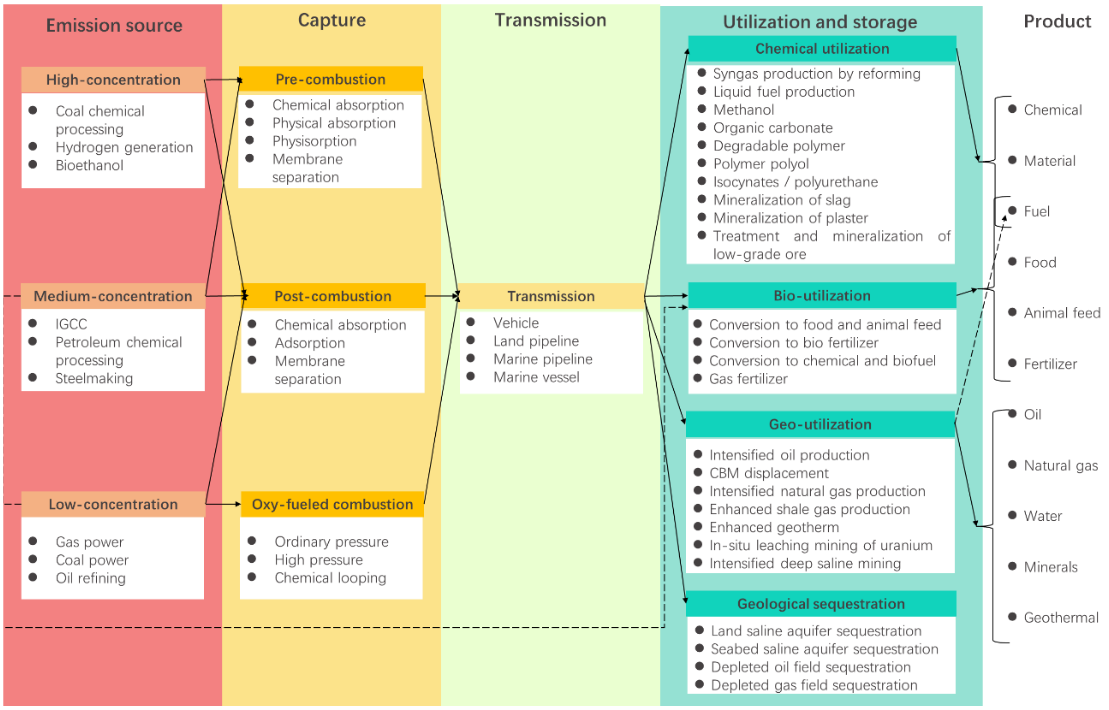


Fig. 19 Schematic diagram of CCUS technology processes and types

Capture

The BF process accounts for more than 50% of greenhouse gas (GHG) emissions in China's iron and steel industry, and together with the coking process, contributes to the direct emission of a vast majority of the CO_2. Thus, the application of CCUS technology in both the processes above provides the best economic benefits for emission reduction in the iron and steel industry [110–112]. Additionally, some scholars have encouraged the construction of a comprehensive exhaust treatment system for CCUS to be adopted throughout a steel plant. However, this scheme is costly and has a lack of practical projects, and it is this not discussed in detail in this report.

Flue gas from combustion is the main source of CO_2 emission in the iron and steel industry. The post-combustion capture of CO_2 from flue gas that comes from coking and BFs is the carbon capture technology most widely used in the iron and steel industry. Theoretically, this technology can be implemented in all existing steel plants and steel plants under construction and with capture plans. Currently, the most commonly used CO_2 separation technologies are chemical absorption (using acid/base absorption), physical absorption (temperature or pressure swing absorption) and membrane separation. Membrane separation technology, which is in development, is recognized as having great potential in terms of energy consumption and equipment compactness [93, 112]. The priority in applying CO_2 capture technology should be based on the possibility of avoiding CO_2 emissions and the difficulty of capture. The former depends on the total CO_2 emissions and the latter is determined by the concentration of CO_2 in the flue gas and the presence of other pollutants. CO_2 in the stream of blast furnace gas accounts for approximately 35% of the total CO_2 emissions from steel plants, and the pre-combustion capture of CO_2 from blast furnace gas is therefore another option to be considered [113, 114].

Pre-combustion capture is mainly used in systems of the integrated gasification combined cycle. This capture converts coal into coal gas through enriched air gasification under high pressure and produces CO_2 and H_2 after a water-gas shift reaction. It will be straight forward to capture CO_2 under a high gas pressure and high CO_2 concentration. The remaining H_2 can be used as fuel. Pre-combustion capture can avoid the disadvantages of a large flue gas flow and a low CO_2 concentration that arise in conventional post-combustion capture and is considered to be one of the most promising carbon capture technology routes. At present, the main CO_2 separation technologies that can be applied to pre-combustion capture are physical absorption and chemical absorption. However, the pre-combustion capture of CO_2 from blast furnace gas can reduce the possibility of capturing CO_2 from flue gas upon combustion.

COURSE50 is taken as an example of the development of carbon capture technology as shown in Fig. 20. In this project, a high-performance chemical absorption liquid has been developed to further improve efficiency. Additionally, unused thermal energy in the CO_2 removal stage is used to further reduce costs. Upon a water-gas shift (whereby CO and H_2O react to generate CO_2 and H_2), blast furnace gas (or coke oven gas) enters the absorption tower to remove CO_2 and the remaining gas returns to the steelmaking reactor. Pre-combustion capture can avoid problems that result from a high content of smoke dust or low CO_2 concentration and affect post-combustion capture. Its main shortcoming lies in that it only partially captures carbon emissions [115].

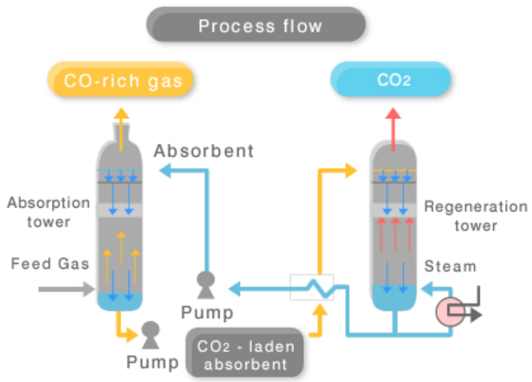


Fig. 20 Typical carbon capture process in the iron and steel industry (taking COURSE50 as an example)

Utilization

The capture of CO_2 that is subject to storage is a carbon reduction technology featuring the butterfly effect. It is necessary to solve problems of infrastructure construction, storage method/area selection and subsequent construction planning in the iron and steel industry. Such capture and storage is a comprehensive project that requires the collaboration of various industries as the technology matures. Thus, Chinese researchers have highlighted the direct use of CO_2 captured in the iron and steel industry and have made achievements in this respect.

CO_2 as a blender gas for steelmaking: Through the substitution of nitrogen, argon and other gases, CO_2 participates in the top blowing/bottom blowing of the converter and the stirring of a ladle of steel melt. CO_2 can react with carbon to generate twice as much CO and it is thus conducive to degassing and removing impurities, reducing iron losses in slag and improving the dephosphorization rate. The disadvantage of CO_2 is a certain oxidizability and the potential to shorten equipment life [116, 117].

CO_2 as a reaction medium for steelmaking: In CO_2–O_2 mixed injection steelmaking, CO_2 can react with elements such as iron, phosphorus and silicon at high temperature, and some reactions have higher priority than the reaction with oxygen. CO_2 can reduce the CO_2 volatilization and oxidation losses caused by the direct impact of oxygen on molten iron. Zhu Rong's team conducted experiments and reduced smoke dust in mixed injection steelmaking by 7.36%–15.72%, reduced lime consumption by 1.8–3 kg, reduced oxygen consumption by 1 m^3, and increased the caloric value of gas [117, 118].

CO_2 as a protective gas for steelmaking: On the basis of the physical and chemical properties of gaseous CO_2 or dry ice, CO_2 participates in steelmaking as a protective gas, partially replacing the function of nitrogen. CO_2 can reduce steel losses, the nitrogen content in finished steel, and the porosity of the finished steel [119].

CO_2 as a raw material of syngas: Syngas, a mixture of CO and H_2, is prepared by adopting coke-oven gas through the dry reforming reaction of CO_2 and CH_4. Syngas then participates in DRI steelmaking or in the preparation of chemical feedstock such as ethanol. Zhou Hongjun's team at China University of Petroleum investigated this technology, which has entered the pilot phase [120, 121].

Transport and storage

The storage and transport of CO_2 captured in the iron and steel industry are similar to those in other industries. In terms of transport, CO_2 is liquefied and transported by pipelines, vehicles, ships and other means of transport. Storage mainly involves the use of a saline aquifer on land, depleted oil and gas reservoir or seabed saline aquifer. Storage is constrained by the construction of the storage space and the corresponding planning of the iron and steel industry [112, 122, 123].

4. Application Potential and Cost Analysis of Hydrogen-energy Steelmaking Technology

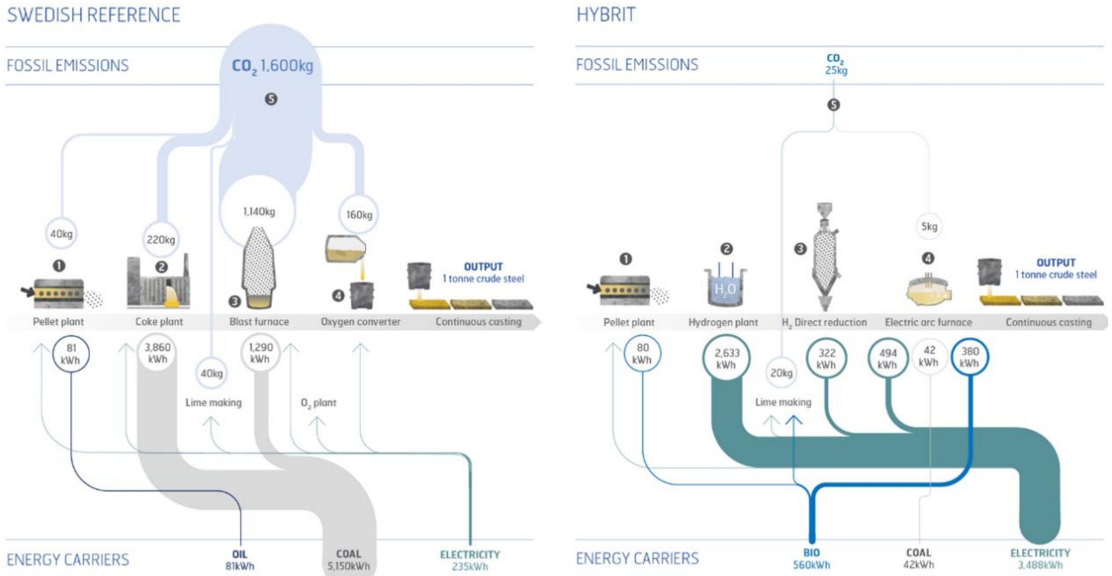
4.1 Overview of Existing Projects/Research Results

4.1.1 Application potential

There are two aspects to the application potential of hydrogen-energy steelmaking, namely the expectation of the overall emission reduction of demonstration projects and the emission status and emissions reduction potential related to hydrogen production technologies.

Approximately 12 GJ of hydrogen is needed to produce 1 ton of hydrogen-based DRI. Researchers have worked out development plans to obtain 400 Mt of hydrogen-based DRI in East Asia. This is equivalent to the reduction of the expected steel output of BF-BOF to 525 Mt by 2035 and to 423 Mt by 2050. This implies a need for approximately 240 GW of electrolyzer capacity. According to this forecast, GHG reductions are expected to be approximately 50 Mt by 2035 and 500 Mt by 2050 [124, 125]. Conversely, if the hydrogen-based DRI-EAF method rather than the BF-BOF route is adopted, CO_2 emissions are expected to be reduced by 80%–95% [105, 126–129].

HYBRIT. An energy flow diagram and the consequent carbon emissions are shown in Fig. 21. For the typical BF-BOF process used in Switzerland, the CO_2 emissions per ton of steel are 1.6 t (approximately 2.0–2.1t for those in other European countries), with comprehensive energy consumption of 5385 kWh. The CO_2 emissions per ton of steel generated using the HYBRIT process are only 25 kg, with comprehensive energy consumption of 4051 kWh; i.e., 98% lower than that of the blast furnace process [95, 96, 130].



Source: http://www.worldmetals.com.cn/viscms/bianjituijianxinwen1277/20180906/245527.html

Fig. 21 Analysis of the energy consumption and emission of the HYBRIT project

COURSE50: Carbon emissions are expected to be reduced by 10% through hydrogen steelmaking technology and by 20% through CCUS technology. In July 2016, the first pilot operation using the pilot blast furnace was performed for a period of approximately 3 weeks. The results show that 9.4% emission reduction can be achieved, close to the emission reduction target of 10%, compared with emissions under the operating conditions without hydrogen injection. This indicates the optimal operating conditions for maximizing the hydrogen reduction effect. It was found that supplying air by injecting hydrogen into the furnace is the key maximizing the hydrogen reduction effect. Additionally, the interlocking operation of sending the blast furnace gas produced by the test blast furnace to the CO_2 separation and recovery test equipment was carried out [98, 101].

H2FUTURE: It is planned that the ultimate goal of reducing CO_2 emissions by 80% will be achieved by 2050 through a combination of hydrogen-making technologies using renewable energies such as wind and solar energy and other engineering improvements [107].

Tsinghua University INET: A simple calculation was made for nuclear hydrogen production and steelmaking. The energy required for the annual output of 1 million tons of steel was estimated as total energy of 2.72×10^7 GJ (870 MWh), thermal energy of 1.7×10^7 GJ (546 MWh) and electric energy of 4×10^6 GJ (130 MWh). One HTR-PM600 can meet all energy requirements for 1.8 million tons of steel per year, including hydrogen, electricity, and heat. In other words, to produce 600 million tons of steel, 400 high-temperature gas-cooled reactors with a capacity of 600,000 kW are required. The corresponding CO_2 emission is 14 kg/t steel, slightly lower than that of the HYBRID project [131].

The above theoretical research and the production practices of demonstration projects reveal that regions differ in terms of actual production conditions and technical choices. Overall, cleaner underlying hydrogen implies a higher carbon reduction potential, with the highest carbon reduction ratio being at least 80%.

In considering the effect of hydrogen energy, the GHG emission reduction potential for different hydrogen energy sources can be analyzed by summarizing the existing hydrogen energy life-cycle GHG emission analysis results both inside and outside China, as shown in Fig. 22 [132–151]. The following judgments can be made. The results of various case studies are scattered and the emission research results for different routes in different national situations are highly uncertain. It can be roughly determined that the hydrogen production route with renewable energy as the source has good potential for low carbon emissions. In the current scenario, the use of grid electricity/fossil fuel to produce hydrogen for steelmaking is not more competitive in terms of GHG emissions than the direct use of coal. Countries should choose optimal transition-stage and final-stage hydrogen production technologies for their development according to their characteristics. It is thus necessary to further research and analyze the Chinese scenario [134, 152].

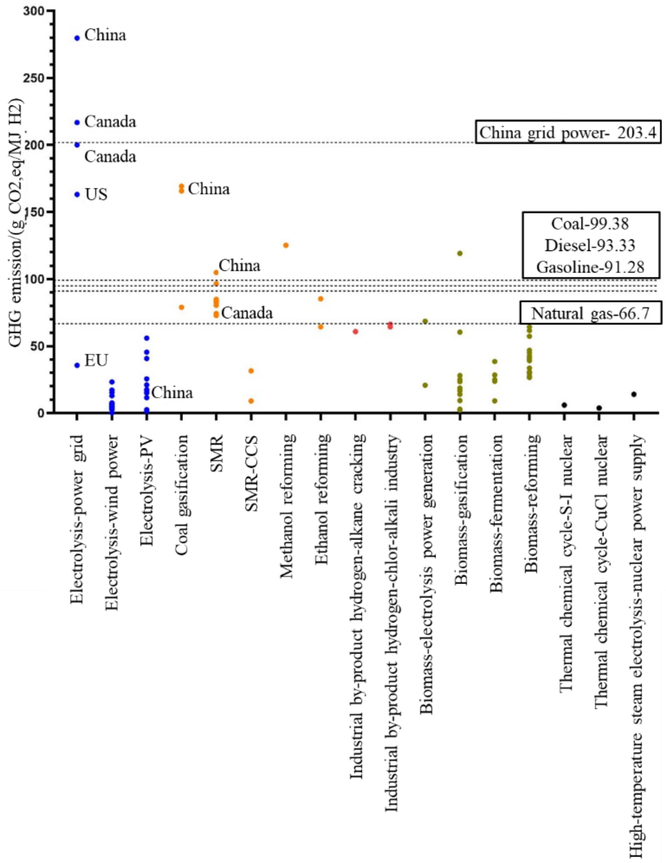


Fig. 22 Results of research on the life-cycle GHG emissions of various hydrogen production technology routes

4.1.2 Carbon reduction costs

HYBRID: According to a report published in early 2018, in the early phase, a total of 30 million euros was invested to build a 240-MW wind power hydrogen production plant and an ironmaking BF. Measured in terms of electricity and coke prices and the CO_2 emission trading price in late 2017, the cost of the hydrogen metallurgy process used in the HYBRIT project was 20%–30% higher than the cost of the traditional BF smelting process adopted in Europe [96].

SALCOS: In the early phase, the Salzgitter wind power hydrogen production project was planned and implemented in Salzgitter, Germany. The idea of the project was to generate electricity using wind power, to produce hydrogen through water electrolysis, and then to transport hydrogen, as a reducing gas, to the cold rolling process and oxygen to the blast furnace for use. For the generation of wind power, seven wind turbine generators with a total generating capacity of 30 MW were built through cooperation with wind power suppliers. Among them, three wind turbine generators were installed at the plant in Salzgitter. According to the project plan, the first step was to build a proton exchange membrane electrolyzer with electrolytic hydrogen production capacity of 400 standard cubic meters per hour, with the distilled water coming from the water purification facility of the steel plant. The second step was to supply the electric power of the wind farm to the water electrolysis plant. The total investment in the construction of wind power generation and hydrogen production plants was approximately 50 million euros. The hydrogen production plant will be put into use in 2025. On this basis, the use of other clean energy sources for electric power generation will be studied. In this project, Linde was responsible for the transportation of hydrogen, which was mainly achieved using automobile gas tanks [95, 96].

INET: China's INET researchers estimated the cost of nuclear steelmaking by referencing the parameters of the direct reduction project of the Japan Atomic Energy Agency. Although hydrogen-reduction steelmaking has not yet been commercialized, an estimation can be made of the price of direct-reduction steelmaking (i.e., the supply price of natural gas and the investment cost of the reformer can be substituted with the price of nuclear hydrogen and the carbon sequestration cost is then subtracted). The result obtained is expressed as a function of the hydrogen price and compared with that of the conventional process. By reference to the 10-year average price of steel during the period 2000–2010, the coke blast furnace process cost US$ 670 per ton of steel and the natural gas reduction process cost US$ 675 per ton of steel. The estimated nuclear hydrogen cost was US$ 2.45 per kg H_2 and the corresponding nuclear steelmaking cost was US$ 628 per ton of steel. Therefore, the nuclear hydrogenation steelmaking process can compete with conventional processes.

Overall, in both the cases of renewable energy hydrogen production for steelmaking and nuclear energy hydrogen production for steelmaking, the high cost of the current infrastructure (e.g., wind power photovoltaic equipment, electrolyzers, and high-temperature gas-cooled reactors) makes the total cost much higher than that of traditional steelmaking. Technological advances and the construction of a carbon market are still required to maximize cost optimization.

4.2 Life-cycle Analysis

4.2.1 Life-cycle modeling of mainstream steelmaking technology routes

The energy consumption and GHG emissions of China's iron and steel industry differ from the global averages. It is thus necessary to better understand the relevant conditions of China through life-cycle analysis. This paper reviews the reports of statistical agencies [6, 153, 154] and other research results [155–168] of China's iron and steel industry regarding energy consumption, material consumption and transport parameters. Notably, for the auxiliary processes in each stage of the development of China's iron and steel industry, such as material transport and handling, their energy consumption and material consumption are considered in each process and not listed separately.

Modeling

We analyze the energy consumption and GHG emissions of China's iron and steel industry using the published data and by applying the author's Tsinghua Life Cycle Analysis Model (TLCAM) [152, 169–173]. This platform was developed using the GREET model framework developed by researchers at the Argonne National Laboratory and adopted a life cycle checklist that applies to China. This analysis method involves multiple stages, such as feedstock extraction and processing, feedstock transport, fuel production, fuel transport and fuel use. The CO_2, N_2O and CH_4 emissions in the TLCAM are converted into the equivalent CO_2 emission according to the global warming potential and are expressed as "CO_2, eq".

Unit material consumption

Unit material consumption means the consumption of raw or auxiliary materials of the process during the production of final products per unit mass (t/t products). The material enrichment rate of each link is comprehensively considered in the determination of unit consumption. The unit construction of ore is taken as an example. Iron ore mining is divided into underground mining and open cast mining. By taking comprehensive account of the ore grade, the material recovery rate of the smelting link and the finished product rate of the processing link, it is found that 1 tonne of vehicle steel is produced using ore mined from underground and open-cast mined ore as feedstock. The required ore input is 3.92 and 4.58 t respectively. In China in 2015, iron ore mined from underground and open-cast mined ore respectively accounted for 23% and 77% of the total iron ore output. It is known that, upon weighing, the average ore consumption per ton of steel products was 4.43 t [155–159, 164].

The specific processes and their unit material consumptions are as follows.

- **BF process:** The BF process is based on the BF and a basic oxygen converter. The feedstock required to produce 1 tonne of crude steel (where the values given here are approximate values) mainly comprises 1400 kg of iron ore, 800 kg of coal, 300 kg of limestone and 120 kg of scrap steel. Approximately 70% of the world's steel is produced via this route.
- **EAF process:** The main feedstock of the EAF process includes scrap steel and/or directly reduced iron or molten iron and electricity. The feedstock required to produce 1 tonne of crude steel (where the values given here are approximate values) comprises 880 kg of scrap steel, 300 kg of iron, 16 kg of coal and 64 kg of limestone. One-hundred percent scrap steel can be used for the EAF route. Approximately 30% of the world's steel is produced via this route.
- **Martin process:** The Martin process accounts for approximately 1% of the world's steel output, and its application is declining owing to its environmental and economic disadvantages.

Scrap steel (up to 35%) is used in the BF process whereas 100% scrap steel can be used in the EAF process. However, no scrap steel can be used when 100% scrap steel is used to reduce iron. Currently, there is not enough recycled scrap steel to produce all new steel from recycled resources.

It is noted that products of the iron and steel industry are simplified into two types without differences, namely section steel and pig iron. Additionally, subdivided materials are no longer strictly tracked.

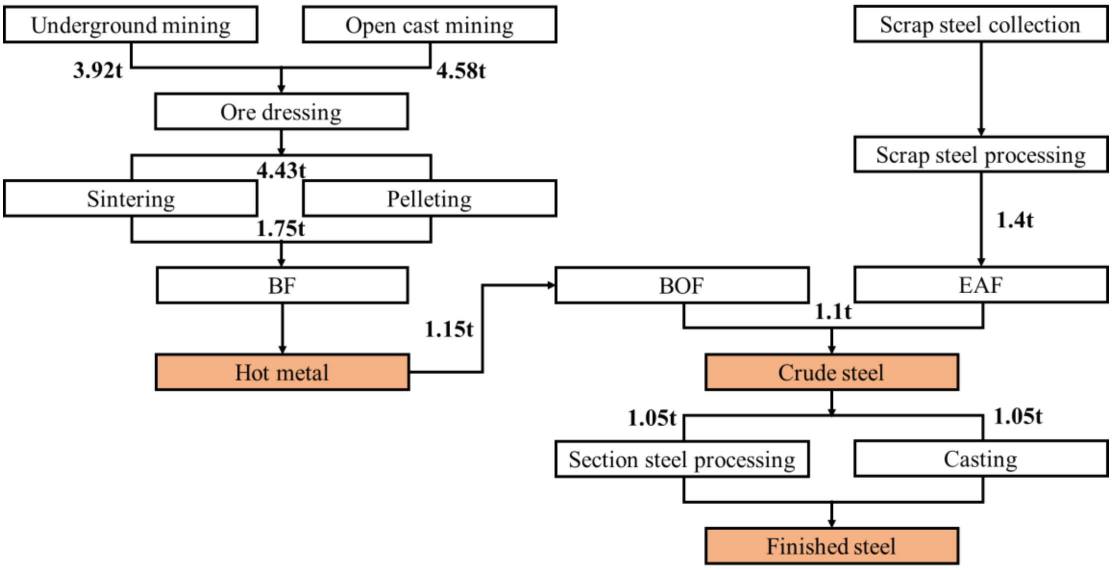


Fig. 23 Production of iron and steel materials and unit process material consumption

Energy consumption intensity

The energy consumption intensity of a process is defined as the direct energy input that is required to produce products per unit mass in the process. Here, products refer to phased products, not necessarily final products of the process. We continue to take iron ore as an example. In 2015, the energy consumption intensity of the ore dressing link in China was 110.4 MJ/t. This means that the energy input required to obtain each ton of iron concentrate is 93.9 MJ, and the energy consumption of the process can be obtained by multiplying the unit consumption and the energy consumption intensity of the process. The energy intensity of the final vehicle steel materials is the sum of the energy consumption for each process [65, 174]. Raw ore is processed into crude steel products upon ore dressing, sintering, pelletizing, blast furnace ironmaking, converter steelmaking and other processes and then further processed to eventually become profiles or castings required for manufacturing automobile parts. Recycled steel materials have a smelting process simpler than that of crude steel. The recycled scrap steel is sent to an electric arc furnace for smelting after being subject to pretreatment processes, such as impurity removal. The results show that the energy consumption of BF ironmaking, coking and electric furnace steelmaking is highest and the corresponding emissions are high (Table 5).

Table 5 Process energy consumption intensity and process fuel structure of steel materials

Process	Energy consumption intensity (MJ/t)	Process fuel structure (%)								
		Coal	Petroleum	Natural gas	Diesel oil	Gasoline	Fuel oil	Electric power	Coke	Gas
Underground mining	40.3	0	0	0	0	0	0	100	0	0
Open cast mining	13.8	0	0	0	77.1	0	0	22.9	0	0
Ore dressing	110.4	0	0	0	0	0	0	100	0	0
Sintering	1448.6	88.	0	0	0	0	0	11.3	0	0

Pelleting	506.7	7 75.1	0	0	0	0	0	24.9	0	0
Blast furnace ironmaking	93.9	0	0	0	7.9	0	0	92.1	0	0
Converter steelmaking	14300.2	26.2	0	0	0	0	0	1.7	72.1	0
Electric furnace steelmaking	255.3	0	0	0	0	0	0	100	0	0
Profile processing	1333.2	0	0	0	0	0	0	100	0	0
Casting	1866.4	0	0	0	0	0	0	21.6	0	78.4

Import, export and transport

In 2015, China's iron ore imports accounted for approximately 87.5% of the total iron ore. For imported iron ore, the energy consumption of the mining process is no longer considered. The transport distance is the average weighted distance from each country of export to China according to the proportion of the iron ore imports in China's iron ore imports. By reference to the statistics of the customs authority and industry associations, the average distance to shore for imported iron ore is taken as 6652 nautical miles. After arriving onshore, the iron ore is transported to steel plants for smelting by railway. For the transport distance, we refer to the average distance of transport by railway, 533 km (the National Bureau of Statistics of the People's Republic of China, 2018). For the mode and distance of the transport of domestic ore, we refer to the imported ore after arriving onshore [154]. We assume that the average distance between the scrap steel distribution center and the steel plant is 500 km and that road transport is used. We assume that the processed steel materials are transported by trucks to a parts plant 200 km away [6].

Analysis results

The GHG emissions from BF converter steelmaking and waste furnace steelmaking in China are 2.10 t CO_2 (eq/tcs) and 0.61 t CO_2 (eq/tcs). During the preparation of the iron material, the GHG emissions for the iron scrap-electric furnace method are 0.3 t CO_2 less than those for the BF-BOF method (eq/tcs). Notably, although China's emissions reported in this study are slightly higher, the methodology in this study is consistent with that of related studies conducted by academic institutions, such as the Worldsteel Association [27, 175–177]. As for the reasons, first, the system boundaries applied in this study are much broader (owing to raw material production and transport) [178, 179]. Second, China's energy emission coefficient differs from the global average and the proportion of electric furnaces in China is lower than the global average (Table 6).

Table 6 Life-cycle GHG emissions of steel materials

	Pig iron	**Crude steel**	**Section**	**Hot-rolled coil**
BF-BOF	1.74	2.10	2.18	2.35
Scrap-EAF	——	0.61	0.70	0.87
Average	1.74	1.93	2.01	2.18

4.2.2 Life-cycle modeling analysis of hydrogen-based DRI

In contrast with the case of traditional steelmaking, for DRI (especially green-hydrogen DRI), changes in the carbon content of molten iron in the iron and steel metallurgy process, the impact of steelmaking solvents (e.g., raw/slaked lime), the amount of ferroalloy added, the crushing/oxidative loss during storage and transport (see Section 3.3.1), and other factors have obvious effects on GHG emissions. Thus, on the basis of the discussion presented in section 4.2.1, this study incorporates these elements into the life-cycle analysis model. By studying the average levels of the iron and steel industry throughout China in 2018, the GHG emissions and production cost for each technical route are obtained, as shown in Figs. 24 and 25. Emissions of the BF-BOF and scrap-EAF routes are slightly higher than those presented in section 4.2.1.

According to the type of reducing agent used, DRI has many production routes, which can be divided into two main categories, namely traditional fossil-fuel DRI and hydrogenated/pure-hydrogen DRI. The reducing agent used for fossil-fuel DRI is mainly natural gas. The process can be further divided into MIDREX-catalytic reforming, HYL-reaction tank catalytic cracking, and the use of HYL-Energiron ZR according to the global main equipment suppliers and production technologies. Examples of reducing agents are coke oven gas and coal DRI. For hydrogenated/pure-hydrogen DRI, in contrast with the natural gas–iron ore reaction, the hydrogen–iron ore reaction is an endothermic reaction in which hydrogen has special characteristics. The addition of hydrogen has complex effects on the raw material characteristic requirements and product properties of the DRI-EAF metallurgical process, the subsequent steelmaking process and the comprehensive energy consumption of ironmaking. Hydrogen is mixed with natural gas/CO in most existing projects. The present study analyzed the cases of full hydrogen (H_2 full), a proportion of ideal hydrogen (H_2 ideal) and a proportion of mainstream hydrogen (H_2 30%).

Additionally, steel production is a complex process that uses diverse equipment and has many influencing factors. To compare technical routes fairly and to draw representative conclusions, this study introduced preconditions for Figs. 24 and 25. In Fig. 24, DRI is fed into the EAF adopting hot delivery and hot charging technology; H_2-DRI is not separately subject to carbon adjustment in the steelmaking step, but rather this is completed in the shaft furnace; the COG-DRI route is an auxiliary facility of the steelmaking plant, not the coking plant; there is only DRI as the raw material in the EAF route and no scrap steel or molten iron; hydrogen is derived from renewable electrolysis in 2018; and the hydrogen storage and transport process uses grid power of China. In Fig. 25, assuming the wage costs are the same, the equipment cost is characterized by the cost difference between DRI and the SF/BF, EAF and BOF for the same production capacity. The electricity price for large industries is set at 0.7 yuan/kWh and that for renewable energy at 0.6 yuan/kWh.

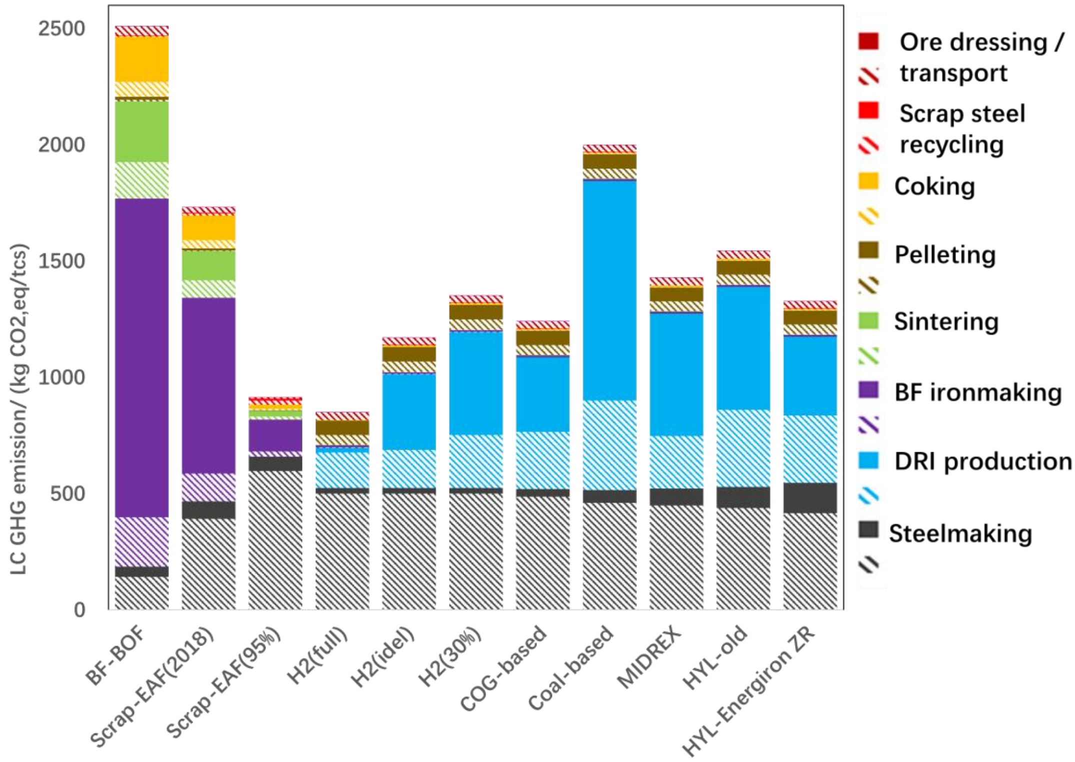


Fig. 24 Life-cycle GHG emissions of mainstream and alternative technology routes for steelmaking

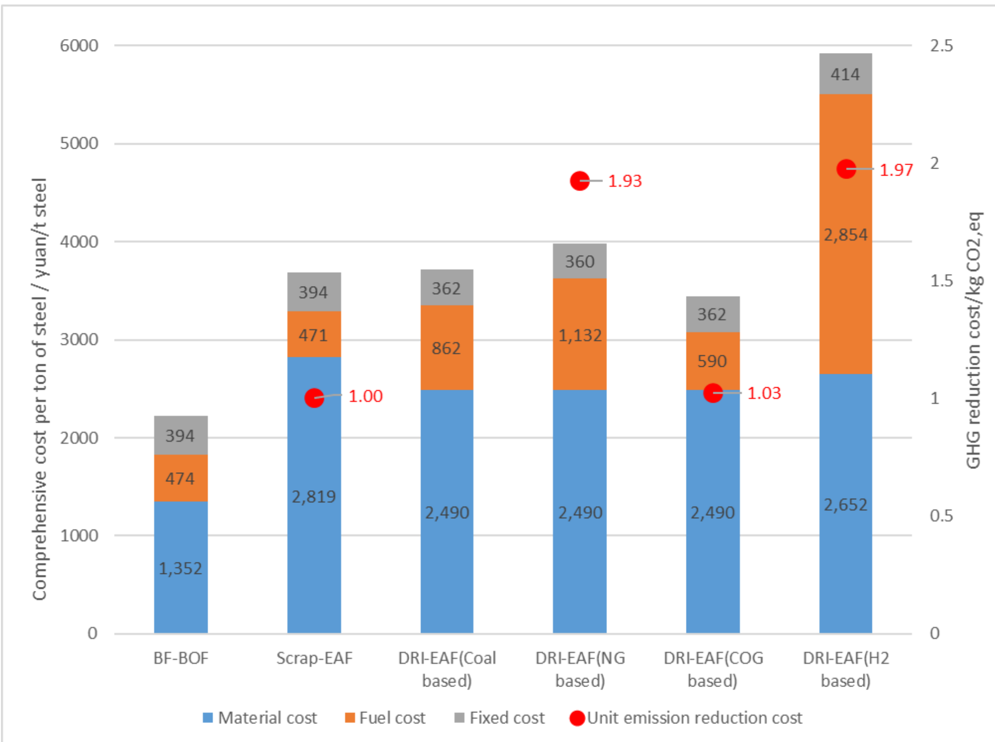


Fig. 25 Levelized cost and carbon reduction cost of mainstream and alterative technology routes for steelmaking

According to Fig. 24, in the current scenario, emissions from the coal-based DRI technology are 2.00 t CO_2, eq/tcs (ton crude steel), lying between those for China's existing EAF steelmaking (1.83 t CO_2, eq/tcs, where a large amount of feedstock is still molten iron) and those for BF-BOF steelmaking (2.51 t CO_2, eq/tcs). Emissions in low-hydrogen (30%) steelmaking are similar to those of COG/natural gas-based steelmaking technology routes, ranging between 1.32 and 1.54 t CO_2, eq/tcs, and 15.7%–27.5% lower than the average level of the current scrap-EAF steelmaking in China. These technology routes can be used as technical choices in the research and design and promotion of gas-based direct-reduction technology, without bringing about additional GHG emissions. Emissions in pure-hydrogen steelmaking (0.85 t CO_2, eq/tcs) are slightly lower than those in ideal scrap-EAF steelmaking (0.91 t CO_2, eq/tcs). Therefore, in attaining China's goal of carbon neutrality by 2060, pure-hydrogen DRI-EAF and scrap-EAF can complement each other to avoid the inconsistency between scrap steel recycling and crude steel needs. Additionally, direct emissions of the pure-hydrogen DRI route are lower than those of the scrap-EAF route. Under the scenario of low carbonization of the whole industry chain, the former is expected to achieve the goal of almost zero emissions.

Figure 19 shows that, owing to the high costs of scrap steel and electricity on the scrap-EAF route, it is difficult to replace the BF-BOF route with the scrap-EAF route. Although the coal-based and natural gas-based DRI-EAF routes have higher fuel costs and equipment costs than the scrap-EAF route, the imported high-quality iron ore required by DRI is still less expensive than the corresponding scrap steel. Consequently, the steelmaking costs of coal-based and natural gas-based DRI-EAF routes can be maintained at a level close to that of the scrap-EAF route. It is thus expected that in the future, the development priorities of these two types of technology will be determined by energy prices and supply–demand conditions, the cost of domestic scrap steel, and the international supply of iron ore. From the perspective of national interests, reducing the cost of scrap steel as soon as possible will help lower the dependence on international iron ore to some extent. Currently, the hydrogen-based DRI-EAF route has a high comprehensive cost and the cost of hydrogen production needs to drop appreciably for the route to be successfully marketed. In terms of the cost of emission reductions, the scrap-EAF route is the best choice. The coal-based DRI-EAF route, which has received attention from Chinese academic and industrial circles, has relatively small advantages in terms of the emission reduction cost.

5. Scenario Analysis of CO2 Emissions in China's Iron and Steel Industry

5.1 Scenario Settings

5.1.1 Scenario of the crude steel demand and the corresponding scenario of scrap steel resources

According to the judgment of China's future steel demand made in Chapter 2, the benchmark scenario and the steel demand control scenario are denoted S1 and S2 respectively.

In combination with China's previous steel demand, quantity of scrap steel resources, amount of scrap steel recycled, and methods of estimating scrap steel resources used in previous studies, scrap steel resources are roughly equivalent to the sum of the recycled amount in the current year (self-produced scrap steel), the 15-year short-term recycled amount and the 50-year long-term recycled amount (social scrap steel), as expressed by

$$O_{fs}\ (t) = (8\% + 6\%)Ocru(t) + 32\%Ocru(t-15) + 60\%Ocru(t-50)$$

Additionally, not all scrap steel resources can be recycled. According to previous data on scrap steel consumption, it is assumed that the availability rates of the three types of scrap steel resources listed above are 0.95, 0.70 and 0.35 respectively. The crude steel demand and quantity of scrap steel resources under S1 and S2 are shown in Fig. 26.

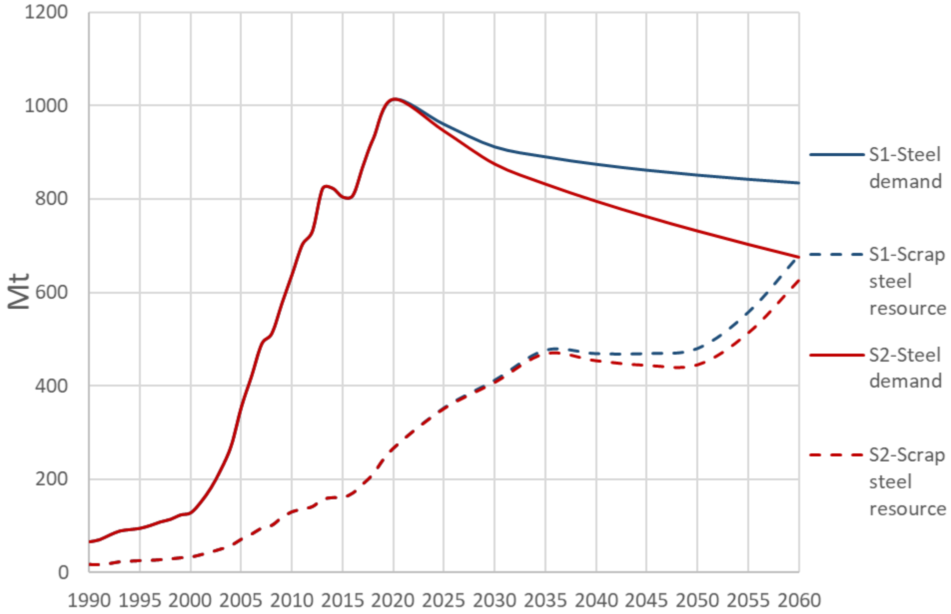


Fig. 26 Crude steel demand and scrap steel resources under two scenarios

5.1.2 Advances in traditional steelmaking technology

On the basis of the technology overviews presented in sections 3.1 and 3.2, this study assumes that by 2060, the existing BF-BOF technology improvements will be fully applied in steel production. In that case, traditional BF-BOF technology will reduce fossil fuel consumption by 20% in the future.

5.1.3 Changes in the proportion of technology

In addition to the benchmark scenario and the steel-savings scenario that describe the steel demand, three additional scenarios for the proportion of technology in the future, denoted A, B and C, are established in this study. Together with the scenarios in section 5.1.1, there are six scenario combinations; e.g., scenario S1-A combines scenarios 1 and A. Scenarios A, B and C are described as follows.

A. Basic scenario of a slow increase in the use of EAFs: The proportion of the use of BOFs decreases by 1% each year. The proportion of the use of EAFs reaches 30% in 2060.

B. Scenario of scrap steel consumption: Steel production is organized with the goal of completely consuming the scrap steel generated in the current year without promoting DRI, and the increase in EAF production capacity is linked with the amount of scrap steel.

C. Scenario of near-zero emissions: Steel production is organized for the purpose of achieving a near-zero scenario as much as possible, which means increasing the proportion of use of EAFs as much as possible and that more DRI production is required to satisfy the demand for EAFs. The proportion of the use of EAFs reaches 90% in 2060.

The remaining parameters in the near-zero-emission scenario are given in Table 7. In this scenario, hydrogen is introduced to the BF to further reduce emissions.

Table 7 Parameters in the near-zero-emission scenario

Technology penetration rate under the near-zero emission scenario	2020	2025	2030	2035	2040	2045	2050	2055	2060
BF introducing hydrogen	0%	0%	2%	5%	10%	17%	25%	30%	40%
EAF proportion of DRI	0%	10%	25%	30%	38%	49%	60%	71%	80%

5.1.4 Future electric power and hydrogen energy structure

For the future energy structure, changes in the electric power structure and hydrogen supply system are mainly considered in this study. For the fossil fuel supply chain, we refer to judgments made in the previous life-cycle study. Technologies in each link of the life cycle of fossil have matured and have little room for improvement. Compared with the effects of electricity and hydrogen on the life cycle of fossil fuel, the effect of related technological improvements is negligible [173]. By reference to the research of the National Development and Reform Commission of China and related literature, the present study adopted the future electricity mix scenarios for China given in Table 8 [180–182].

Table 1. Electricity mix scenarios in China (%)

Items	**Coal electricity**	**Gas electricity**	**Oil electricity**	**Nuclear electricity**	**Biomass**	**Hydro**	**Other**
2020	60.44	6.32	0.02	4.28	2.29	14.78	12.48
2030	38.85	4.79	0.02	3.94	2.34	15.26	35.76
2040	14.49	3.76	0.01	3.91	3.12	13.29	61.40
2050	6.83	3.07	0.01	4.27	4.20	14.39	67.23
2060	3.00	2.00	0.00	4.50	4.50	11.00	75.00

Note: "Other" includes wind, photovoltaic, tidal, and geothermal power.

The proportion of China's hydrogen supply chain is also important in predicting the effect of emissions in the iron and steel industry. We obtained forecasts from the report entitled *White Paper on China's Hydrogen Energy and Fuel Cell Industry* and made a further expansion on the basis of the results. In this white paper, the industry-wise demand for hydrogen was judged and the proportion of hydrogen supplied under the scenario of carbon neutrality in China was designed. The proportion of hydrogen production from renewable water electrolysis will increase from 3% in 2020 to 70% in 2060. It is estimated that the proportion of hydrogen production from fossil fuels will gradually drop from 67% in 2020 to 20% in 2050. The by-product hydrogen will account for 30% in 2020 and is expected to drop to 25% in 2040. It is predicted that 10% of hydrogen in 2060 will be derived from new technologies [183]. The present study improved the scenarios of the hydrogen energy supply chain by combining the practical resource constraints of various hydrogen-energy technology routes in the total demand judged in the white paper and various research results.

The NG-based pathway is the most cost-effective hydrogen production method available today, and we thus assume that in the future, the SMR hydrogen output will slightly increase and then remain stable, accounting for half of fossil fuel hydrogen output by 2060, with centralized NG-based pathway, which has high cost performance, being the mainstream technology. Assuming that the existing coal-to-hydrogen fluidized bed capacity is gradually reduced, the coal-to-hydrogen fluidized bed will be replaced by the entrained bed in 2040, which will become the mainstream in 2060. The COG by-product hydrogen will basically decrease with a decrease in the proportion of the BF-BOF route in China. According to the judgment of the IEA, China's crude steel output will decrease from a previous 1.08 billion tons to 710 million tons in 2060 and the BF-BOF will contribute 16% of China's total crude steel output at that time. It is thus judged that the COG by-product hydrogen resources will gradually decrease from 10.3 to 3.7 million tons [184, 185]. The chlor-alkali industry is determined by the demand for polyvinyl chloride and caustic soda to a large extent. China's polyvinyl chloride industry is almost saturated and the demand for caustic soda may increase slightly with the development of electrolytic aluminum, tempered glass and other industries. We thus judge that the hydrogen by-product resources in the chlor-alkali industry will remain at 800,000 to 1 million tons [186]. During the promotion stage of hydrogen energy, grid-based hydrogen production will be a mainstream choice. Following the development of renewable energy and the improvement of hydrogen energy storage and transport technology, the proportion of renewable energy will rise. It was assumed in this study that grid-based hydrogen output will account for 10% of the total hydrogen energy in 2060 and the proportions of wind power generation and photovoltaic power generation in hydrogen production from renewable energy will be consistent with the respective resources and development levels in China. On the basis of the above judgments and assumptions, the development scenarios of hydrogen energy technology adopted in this study are shown in Fig. 27.

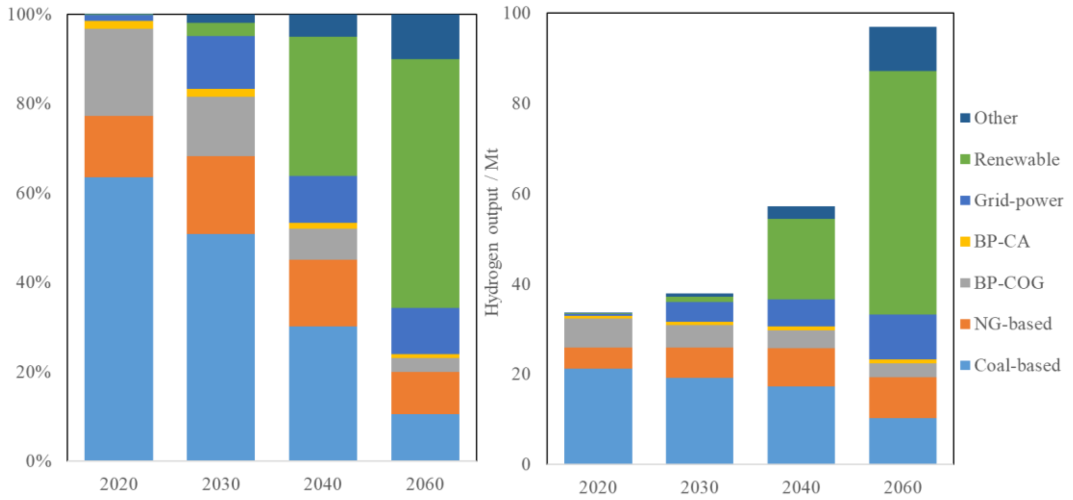


Fig. 27 Scenarios of hydrogen-energy supply-chain technology adopted in this study

The GHG emissions of various hydrogen production routes in the future are obtained by combining the above scenario parameters and the hydrogen energy system analysis model of our research team, as shown in Fig. 28. The bars for the same year represent gas-to-hydrogen, coal-to-hydrogen, grid-to-hydrogen, hydropower-to-hydrogen, renewable-energy-to-hydrogen, coke oven gas byproduct hydrogen, and by-product hydrogen from the chlor-alkali industry. The error bars on the histogram represent the errors introduced by different hydrogen production, storage and transport technologies. The upper boundary is generally liquid hydrogen storage and transport and the lower boundary is normally pipeline transport.

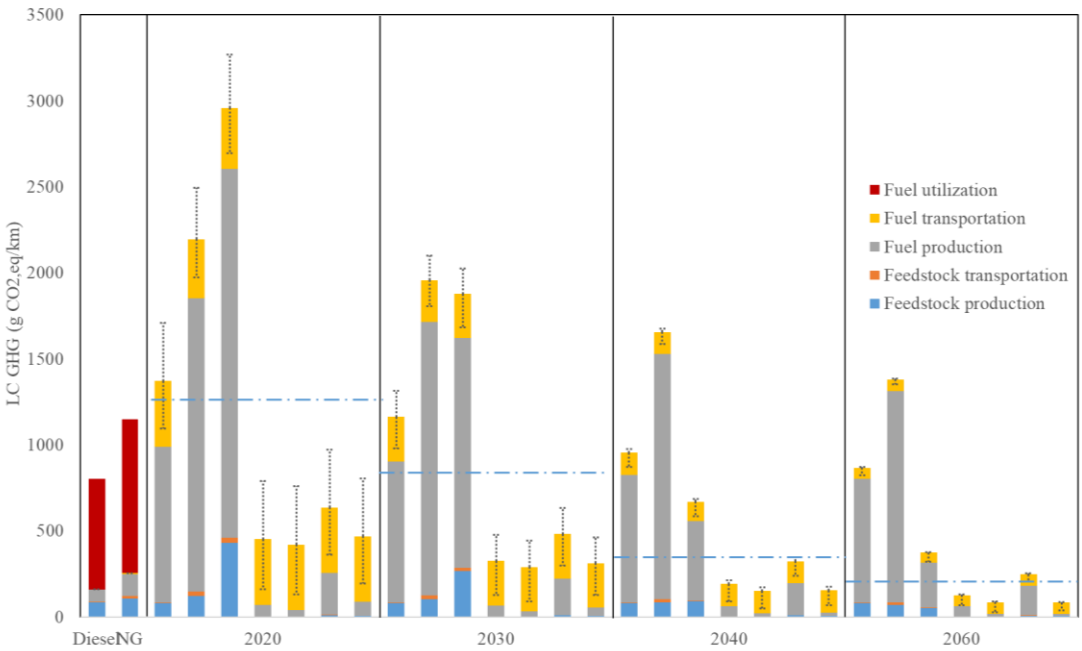


Fig. 28 GHG emissions from hydrogen production

5.2 Scenario Analysis Results

5.2.1 Life-cycle analysis results

Life-cycle analysis provides the demand forecast and scenario design and changes in GHG emissions of China's steel sector in different future scenarios, as shown in Fig. 29. It is first noted that, according to the life cycle research boundary of this study, GHG emissions of China's steel sector in 2020 was 2395 Mt, slightly higher than the results of the Worldsteel Association because the present study accounted for the limestone process, the carbon content of steel, the material transport process, and other factors.

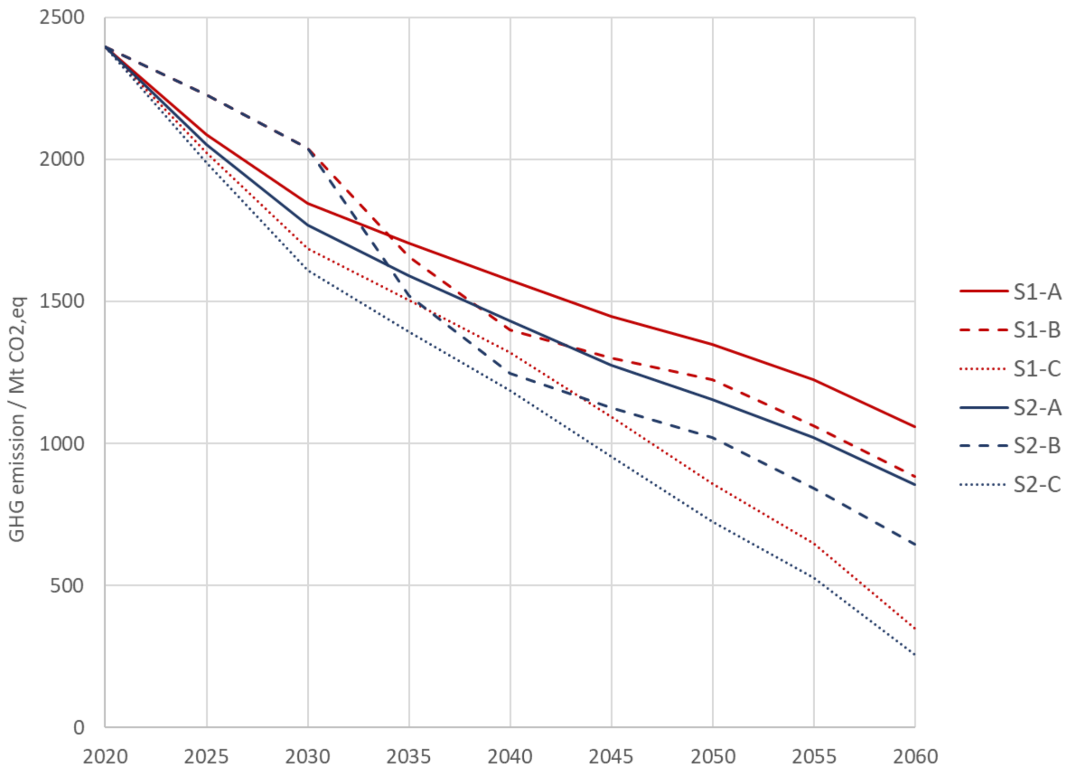


Fig. 29 GHG emissions of China's steel sector in various scenarios

1. In benchmark scenario S1-A, the total GHG emissions of China's iron and steel industry are expected to drop by 56.1%, which is mainly driven by the following factors. First, there is a decline in the crude steel demand. Second, owing to the increase in scrap steel resources, the proportion of use of EAFs increases to approximately 30% and the low carbonization of electric power promotes the development of the entire industry chain. On this basis, the proportion of use of EAFs is 64.3% less in 2060 than that in 2020 for the S2-A scenario, which further reduces demand. However, there remains a gap with the goals of a carbon peak and carbon neutrality. Additionally, it is difficult to fully consume scrap steel resources in this scenario, which may cause waste.

2. In scenarios S1-B and S2-B, which only rely on the rapid promotion of the use of EAFs and focus on the full consumption of scrap steel resources, the proportion of use of EAFs will respectively be 63.1% and 72.2% less in 2060 than in 2020. However, the fast EAF promotion in both scenarios may slightly increase the total life cycle emissions within a period of time, thereby reducing the cumulative emission efficiency. Therefore, EAF promotion requires a combination of the actual utilization of China's future renewable energy and scrap steel resources for dynamic decision making.

3. In near-zero emission scenarios S1-C and S2-C, comprehensive emissions are reduced by 85.4%–88.9% in 2060. Relative to scenarios A and B, scenario C sees a higher emission reduction and cumulative emission reduction in the current year and the full consumption of scrap steel based on the precondition that high financial costs are paid. The emission reductions of S1-C and S2-C in the current year do not differ much, which means that the emission reduction benefits of further controlling steel demand are not appreciable at this time. In other words, if economic, social and other factors lead to a slow decrease in steel demand, more

active technology promotion policies can be adopted to ensure the goals of a carbon peak and carbon neutrality are realized.

5.2.2 Direct emission results

Figure 19 presents the resulting trend of emissions changes when only direct emissions from the iron and steel industry (or steel plants) are considered. Direct GHG emissions from the steel sector in 2020 were 1736.7 Mt. In scenarios S1-A and S2-A, direct GHG emissions can decrease by 880.9–713.1 Mt and it is difficult to eliminate the remaining direct emissions, which requires CCUS technology. In scenarios S1-B and S2-B, direct emissions can be reduced to 828.7–609.3 Mt in 2060. It is seen that compared with scenarios S1-A and S2-A, scenarios S1-B and S2-B do not see the due emission reduction benefits of paying the costs of or constructing EAFs and the related scrap steel recycling system. Achieving the goals of a carbon peak and carbon neutrality still relies on CCUS technology. Additionally, GHG emissions in scenarios S1-C and S2-C can be reduced to 170.9–131.4 Mt, which basically eliminates the reliance on CCUS.

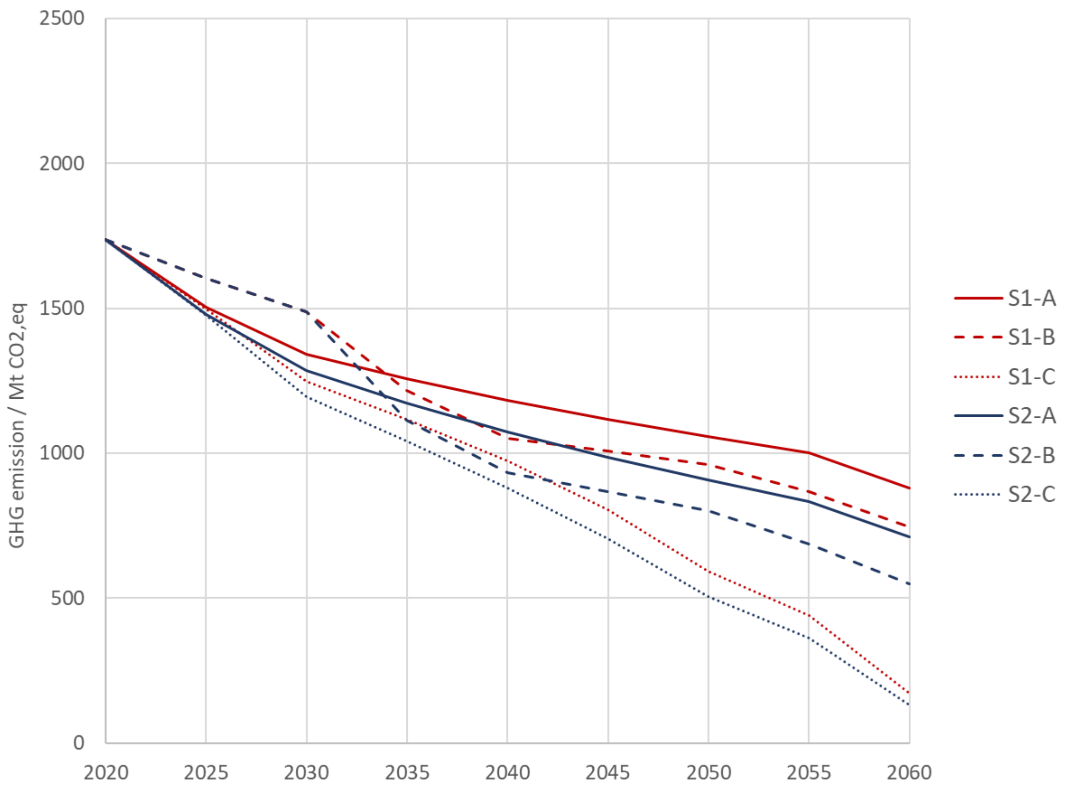


Fig. 30 Direct GHG emissions of China’s steel sector in various scenarios

6. Conclusions

6.1 Judgment on the Low-carbon Development of China’s

Iron and Steel Industry

Pressures on the low-carbon development of steel

- **Large output, high emissions**: China, as the world's factory, contributes more than half of the world's steel output. As industrialization and urbanization continue, the domestic demand for steel will further increase.
- **Low proportion of short-process steel:** Constrained by national conditions, the proportion of short-process steel in China's iron and steel industry is too low and will be difficult to increase within a short period of time.
- **Insufficient degree of centralization**: Small and medium-sized steel enterprises still account for approximately 20% of the production capacity, increasing the average energy consumption/emissions.
- **Risks of excess capacity and inventory**: Stimulus policies adopted in response to the economic crisis have generated greater excesses of capacity and inventory.
- **Risks of industrial transfer and shrinking international trade**: Conservatism in countries led by the United States prevails, which encourages the return of industries to the shores of those countries. Underdeveloped regions gradually participate in the market following their economic growth.

Other process improvement technologies with great potential

- **More improvement technology choices with great potential for comprehensive emissions reduction**: In terms of both consumer and production ends, there are many energy-saving and carbon-reducing technology choices at all stages of the steel production process. Theoretically, the reduction in total emissions due to improvements of mainstream processes can reach 43%.
- **Improved technologies with excellent cost-effectiveness:** Residual heat and residual air recovery and reuse during the ironmaking stage and improved technologies during the rolling/casting stage can reduce emissions while improving production efficiency, with better cost performance.

Zero-carbon technologies having attracted much attention and having their own advantages

- **High versatility of CCUS technology**: Regardless of the traditional blast furnace/converter steelmaking process or coke oven gas/syngas direct reduction process, CCUS technology can greatly reduce the carbon emissions of each process.
- **Low material consumption of the hydrogen energy steelmaking technology**: Compared with the material consumption of carbon capture and storage processes and the material and land consumption for storage device construction, materials of hydrogen-energy steelmaking technology are mainly consumed in equipment manufacturing and they are consumed less.
- **High emission reduction benefits of clean electric power:** In addition to providing emission reduction benefits for hydrogen-energy steelmaking technology, the development of clean electric power can greatly reduce the energy consumption and carbon emissions of short-process steel, resulting in the expectation that short-process steel will be the zero-carbon technology of choice in the iron and steel industry.

6.2 Potential Application Prospects and Effects of Hydrogen

Energy

Technology

Emissions of coal-based DRI technology are higher than the average emissions of China's current EAF steelmaking process, meaning that the former is not suitable for short-term promotion.

Emissions in low-hydrogen (30%) steelmaking are similar to those of the COG/natural gas-based steelmaking technology route and 15.7%–27.5% lower than the average for China's existing scrap-EAF steelmaking. These technology routes can be used as technology choices in the research and promotion stages of gas-based direct reduction without resulting in additional GHG emissions.

Emissions from pure-hydrogen steelmaking are less than those from ideal scrap-EAF steelmaking. Therefore, considering China's goal of achieving carbon neutrality in 2060, the complementary adoption of pure-hydrogen DRI-EAF and scrap-EAF routes can address the lack of coordination between scrap steel recycling and the crude-steel demand. Additionally, the direct emissions of the pure-hydrogen DRI route are lower than those of the scrap-EAF route. Near-zero emissions are expected to be achieved through the low carbonization of the whole industry chain.

Costs

Owing to the high costs of scrap steel and electric power on the scrap-EAF route, it is difficult to truly replace the BF-BOF route with the scrap-EAF route.

The steelmaking costs of coal-based and natural gas-based DRI-EAF routes can be maintained at a level similar to the cost of the scrap-EAF route. It is seen that the development priorities of these two types of technology will be determined by energy prices and supply–demand conditions, the domestic scrap steel cost and the international supply of iron ore. From the perspective of national interests, reducing the cost of scrap steel as soon as possible will help lower the dependence on international iron ore to some extent.

The comprehensive cost of the hydrogen-based DRI-EAF route is high and the cost of hydrogen production has the potential to drop appreciably. It will then be possible to market the route successfully.

The scrap-EAF route is the best choice. The coal-based DRI-EAF route, which has received attention from Chinese academic and industrial circles, has relatively small advantages in term of the emission reduction cost.

Macroscale developments

Promotion of advanced technologies required for achieving the goals of a carbon peak and carbon neutrality: In a relatively conservative technological development scenario, emissions can be reduced by approximately 50%, depending on the decrease in demand and the low carbonization of electric power. However, there remains a gap from the goals of a carbon peak and carbon neutrality. In this scenario, it is difficult to consume scrap steel resources, which may result in the waste of resources. Additionally, a large uncertainty in the decrease in iron and steel demand may make it difficult for conservative technology promotion strategies to achieve the goal of emission reductions.

Promotion of EAF considered from many aspects: The EAF should be comprehensively promoted and designed considering the scrap steel resources, energy structure and technological developments. An excessively aggressive EAF promotion strategy may lead to a short-term increase in emissions and also a weakened response of the iron and steel industry to the fluctuations of scrap steel resources.

Combining hydrogen metallurgy and the EAF to realize the goals of a carbon peak and carbon neutrality: A combination of hydrogen metallurgy and the EAF is expected to reduce emissions by 85.4%–88.9%.

6.3 Policy Suggestions on the Low-carbon Development of the Iron and Steel Industry

The reduction of the CO_2 emissions of China's iron and steel industry can be divided into two stages, namely the short-term emission reduction and long-term emission reduction. The following suggestions are proposed for the following two stages.

Short-term emission reduction

- Improve the management of the iron and steel industry, reasonably organize the production of the industry, increase the concentration of the industry, and eliminate outmoded production capacity.
- Continue to promote the research, development and popularization of steel process improvement technologies and strive to reduce the energy consumption and emissions for the existing steel output to the levels of developed countries.
- Encourage scrap steel recycling, promote the construction of recycling industry, and make preparations for the potential risks of excess capacity, excess inventory, industrial transfer and shrinking international trade.

Long-term emission reduction

- Promote the replacement of traditional energy sources such as coal and coke with renewable energy in the iron and steel industry and adjust the energy structure, laying a foundation for the zero carbonization of electric furnace steelmaking/hydrogen-energy steelmaking.
- Implement multiple technology routes at the same time, promote the strategic analysis and construction planning of hydrogen-energy steelmaking and EAF technologies, and comprehensively consider the crude-steel demand, resource constraints, energy system and social and economic factors to avoid possible problems brought by excessively radical or simple technology promotion strategies.

CO_2 emission reduction in iron and steel production is a comprehensive task. It is necessary to strike a balance between internal and external factors that relate to the development of steel enterprises and environmental policies, which is an issue to be seriously considered by the iron and steel industry.

6.4 Policy Suggestions on the Low-demand Development of Steel

It is necessary to reduce the demand for steel in the automobile, construction, machinery and other manufacturing industries by focusing on three aspects, namely social and cultural factors, infrastructure and technology application. Policies should be implemented in terms of avoidance, transfer and improvement.

Avoidance: Reduce trips (person × km), reduce car ownership and sales and steel for cars; reduce living spaces; improve the sharing economy for products and services.

Promotion: Develop low-speed transport; pursue centralized residence; make efficient use of materials.

Improvement: Manufacture light-weight vehicles; develop alternative low-carbon materials for buildings.

The above analysis and forecast results show that if we want to achieve the goal of controlling steel output at less than 70,000 t in 2060, the low-demand scenario is the most needed in China. Specifically, the following policy measures should be promoted in the construction, machinery and automobile industries, which have a huge demand for steel.

For the construction industry, considering the large-scale growth of new housing areas of China since the reform and opening up of China, it is necessary to reduce the number of large-scale new housing projects approved in urban planning. Additionally, because steel is a recyclable material, we would speed up technological innovation in the use and recycling of steel in the construction industry and provide preferential policies and subsidies for financing quotas for construction units that use recycled steel in construction.

For the machinery industry, after vigorously developing the machinery industry from 2022 to 2025, we must gradually reduce excess production capacity to prevent industry bubbles. For the development of the machinery industry, it is necessary to promote technological progress and lower the demand for steel per unit production capacity. The government should encourage enterprises to replace steel with new materials and offer technical support in the early stage. Additionally, there are many state-owned and central enterprises in the machinery industry. The government should encourage private enterprises to enter the market to give full play to the role of enterprises in independently reducing costs and improving efficiency in an environment of market competition.

For the automobile industry, while vigorously developing new-energy vehicles, we should offer similar policy support to vehicle manufacturers who are using new materials. The reduction of steel consumption, like the transformation of automobile energy, requires the attention of the government and enterprises.

6.5 Policy Suggestions on the Technological Development of the Iron and Steel Industry

In terms of the technology strategy, it is essential to advance multiple technical routes at the same time. It is difficult to achieve the goals of a carbon peak and carbon neutrality by only relying on the improvement of traditional production technology. There will still be problems in terms of direct emissions in the end if we only rely on the construction of a scrap steel recycling system and the promotion of EAF technology. Incorporating hydrogen metallurgy technology into the technology system can greatly reduce direct emissions and thus reduce the reliance on CCUS technology.

In terms of hydrogen-energy steelmaking, it is suggested to select different technical routes at different stages. During the stage of technology research and design and promotion, the coke oven gas and natural gas-based hydrogen-energy steelmaking and direct-reduction ironmaking technologies are most competitive in terms of emissions and costs. Pure-hydrogen steelmaking and enriched-hydrogen steelmaking are not suitable for promotion at this time owing to their immature technologies and high upstream emissions.

In terms of development strategy, it is suggested to adopt a technology promotion strategy that adapts to local conditions and circumstances. The application effect of hydrogen energy steelmaking is associated with the availability of local scrap steel, the energy system and the prices of scrap steel and imported ore. The application effect of CCUS is related to the remaining equipment lifetime and the carbon sequestration and injection capacity of local iron and steel enterprises. The application costs and emission reduction effects of the two technologies are related to their respective technological developments. It is seen that for iron and steel enterprises under different conditions, not all optimal technology development strategies at different time nodes are the same. Additionally, it is necessary to adapt measures to local conditions and circumstances.

References

[1] The World Steel Association(WSA). Steel statistical yearbook 2019. Brussels, Belgium2019.

[2] The World Steel Association(WSA). Steel statistical yearbook 1990. Brussels, Belgium1991.

[3] The World Steel Association(WSA). Steel statistical yearbook 2000. Brussels, Belgium2001.

[4] The World Steel Association(WSA). Steel statistical yearbook 2010. Brussels, Belgium2011.

[5] Energy Transitions Commission (ETC), Rocky Mountain Institute (RMI). China 2050: A Fully Developed Rich Zero-Carbon Economy. 2019.

[6] Editorial Board of China Steel Industry Yearbook(2018). China Steel Yearbook. Beijing: China Metallurgical Press; 2019.

[7] Huang J, Liu J, Zhang H, Guo Y. Sustainable risk analysis of China's overseas investment in iron ore. Resources Policy. 2020;68:101771.

[8] Jiang H-D, Hao W-T, Xu Q-Y, Liang Q-M. Socio-economic and environmental impacts of the iron ore resource tax reform in China: A CGE-based analysis. Resources Policy. 2020;68:101775.

[9] Song L, Wang P, Hao M, Dai M, Xiang K, Li N, et al. Mapping provincial steel stocks and flows in China: 1978–2050. Journal of Cleaner Production. 2020;262:121393.

[10] Pan S-Y, Adhikari R, Chen Y-H, Li P, Chiang P-C. Integrated and innovative steel slag utilization for iron reclamation, green material production and CO2 fixation via accelerated carbonation. Journal of Cleaner Production. 2016;137:617-31.

[11] Zhang Q, Xu J, Wang Y, Hasanbeigi A, Zhang W, Lu H, et al. Comprehensive assessment of energy conservation and CO2 emissions mitigation in China’s iron and steel industry based on dynamic material flows. Applied Energy. 2018;209:251-65.

[12] Wang X, Zhang Q, Xu L, Tong Y, Jia X, Tian H. Water-energy-carbon nexus assessment of China’s iron and steel industry: Case study from plant level. Journal of Cleaner Production. 2020;253:119910.

[13] Quader MA, Ahmed S, Ghazilla RAR, Ahmed S, Dahari M. A comprehensive review on energy efficient CO2 breakthrough technologies for sustainable green iron and steel manufacturing. Renewable and Sustainable Energy Reviews. 2015;50:594-614.

[14] Yellishetty M, Mudd GM, Ranjith PG, Tharumarajah A. Environmental life-cycle comparisons of steel production and recycling: sustainability issues, problems and prospects. Environmental Science & Policy. 2011;14:650-63.

[15] Rissman J, Bataille C, Masanet E, Aden N, Morrow WR, Zhou N, et al. Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. Applied Energy. 2020;266:114848.

[16] Cavaliere P. Direct Reduced Iron: Most Efficient Technologies for Greenhouse Emissions Abatement. Clean Ironmaking and Steelmaking Processes: Efficient Technologies for Greenhouse Emissions Abatement. Cham: Springer International Publishing; 2019. p. 419-84.

[17] Duarte PE, Becerra J, Lizcano C, Martinis A. ENERGIRON direct reduction technology-

economical, flexible, environmentally friendly. Acero LatinoAmericano. 2008;6:52-8.
[18] Antonio Elliot. MIDREX® Direct Reduction Plants – 2019 Operations Summary. 2020.
[19] Vincent F. Chevrier. Ultra-Low CO2 Ironmaking: Transitioning to the Hydrogen Economy. 2020.
[20] Burke P. HIsmelt direct smelting technology. Bhubaneswar, India: International Convention on Clean, Green and Sustainable Technologies in Iron and Steel Making2009.
[21] Liu Y, Qing S, Liu Y, Zhang A, Gui Z. Numerical simulation and experimental study of smelting reduction furnace based on oxygen-rich top-blowing. Acta Technica CSAV (Ceskoslovensk Akademie Ved). 2017;62:231-40.
[22] The World Steel Association(WSA). Energy use in the steel industry. Brussels, Belgium2019.
[23] Sun W, Wang Q, Zhou Y, Wu J. Material and energy flows of the iron and steel industry: Status quo, challenges and perspectives. Applied Energy. 2020;268:114946.
[24] Krüger A, Andersson J, Grönkvist S, Cornell A. Integration of water electrolysis for fossil-free steel production. International Journal of Hydrogen Energy. 2020.
[25] Yang W, Cao J, Wang X-h, Xu Z-r, Yang J. Investigation on Non-Metallic Inclusions in LCAK Steel Produced by BOF-LF-FTSC Production Route. Journal of Iron and Steel Research, International. 2011;18:6-12.
[26] Wei H. Carbon Emissions Analysis of China's Steel Industry Based on Low Carbon Perspective. Fuzhou: Fuzhou University; 2014.
[27] Long W, Wang S, Lu C, Xue R, Liang T, Jiang N, et al. Quantitative assessment of energy conservation potential and environmental benefits of an iron and steel plant in China. Journal of Cleaner Production. 2020;273:123163.
[28] An R, Yu B, Li R, Wei Y-M. Potential of energy savings and CO2 emission reduction in China’s iron and steel industry. Applied Energy. 2018;226:862-80.
[29] Li Y, Zhu L. Cost of energy saving and CO2 emissions reduction in China’s iron and steel sector. Applied Energy. 2014;130:603-16.
[30] Gao X, Wang A. Prediction of steel demand in China based on 's' law. Journal of the Earth 2010; 31:645-52.
[31] Zhang Y, Chen Q, YU W-j, LIU Q-y, LI Y, TAN H-c. Global iron ore supply and demand trend analysis, 2015-2040. Resources Science. 2015;37:921-32.
[32] Hatayama H, Daigo I, Matsuno Y, Adachi Y. Outlook of the world steel cycle based on the stock and flow dynamics. Environmental science & technology. 2010;44:6457-63.
[33] Region M. worldsteel Short Range Outlook of consumption. Steel Times International. 2011:27.
[34] GAO C-k, WEI Y-x, Zhou Y, ZHANG M-h. Analysis of the Driving Forces of Influence Factors on China’s Steel Output. DEStech Transactions on Environment, Energy and Earth Sciences. 2016.
[35] Lin GU, Jing-Tao LI. A Short-term Prediction Research on China's Crude Steel Apparent Consumption after Entering the Peak Area. Value Engineering. 2016.
[36] Peng T, She Y, Yan Y. Prediction study on steel demand of china based on cointegration and grey system theory. Mathematics in Practice and Theory. 2011;41:102-8.
[37] Wang Y, Xu X. Prediction of steel production in China based on wavelet transform and DGM (2,1). Collection. 2019;3.

[38] Shu Fuhua, Ma Yongjun. The Application of Calman Filter Algorithm in predition of China's steel production. Journal of Xuzhou Institute of Engineering (NATURAL SCIENCE EDITION). 2018;33:8-12.
[38] Shu F , Ma Y. Application of Kalman filter algorithm in steel output prediction in China. Journal of Xuzhou University of Technology (Nat. Sci. Edition) 2018;33:8-12.
[39] Research Group on Capacity and Demand Forecasting of China Iron and Steel Industry. Association analysis on the current situation of steel production capacity and the demand trend of steel varieties. China's Steel Industry. 2008.

[40] Liu T, Zhou W, Wang Q. China's iron ore demand forecasting model based on iron and steel production process. Metal Mines 2007:6-8.
[41] long B, Ye J. China's steel and iron ore demand forecast. China Mining. 2010:4-6.
[42] Zhang H. SUSTAINABLE UTILIZATION OF SCRAP IRON AND STEEL RESOURCE IN CHINA. China Population, Resources and Environment. 2003.
[43] China Metallurgical Industry Planning and Research Institute (MPI) will soon release the 2020 China Steel Blue Book series report. Metallurgical Economy and Management 2019:1.
[44] Zhou N, Fridley D, Khanna NZ, Ke J, McNeil M, Levine M. China's energy and emissions outlook to 2050: Perspectives from bottom-up energy end-use model. Energy Policy. 2013;53:51-62.
[45] Hasanbeigi A, Jiang Z, Price L. Analysis of the Past and Future Trends of Energy Use in Key Medium- and Large-Sized Chinese Steel Enterprises, 2000-2030. United States2013.
[46] Chen W, Yin X, Ma D. A bottom-up analysis of China's iron and steel industrial energy consumption and CO2 emissions. Applied Energy. 2014;136:1174-83.
[47] Ma D, Chen W, Yin X, Wang L. Quantifying the co-benefits of decarbonisation in China's steel sector: An integrated assessment approach. Applied Energy. 2016;162:1225-37.
[48] Yin X, Chen W. Trends and development of steel demand in China: A bottom–up analysis. Resources Policy. 2013;38:407-15.
[49] Xuan Y, Yue Q. Forecast of steel demand and the availability of depreciated steel scrap in China. Resources, Conservation and Recycling. 2016;109:1-12.
[50] Zhang S, Yi B-W, Worrell E, Wagner F, Crijns-Graus W, Purohit P, et al. Integrated assessment of resource-energy-environment nexus in China's iron and steel industry. Journal of Cleaner Production. 2019;232:235-49.
[51] Tan X, Li H, Guo J, Gu B, Zeng Y. Energy-saving and emission-reduction technology selection and CO2 emission reduction potential of China's iron and steel industry under energy substitution policy. Journal of Cleaner Production. 2019;222:823-34.
[52] Hanaoka T, Masui T. Co-benefit reductions of short-lived climate pollutants and air pollutants by 2050 while achieving the 2 degree target in Asia. Journal of Sustainable Development of Energy, Water and Environment Systems. 2018;6:505-20.
[53] Wen Z, Meng F, Chen M. Estimates of the potential for energy conservation and CO2 emissions mitigation based on Asian-Pacific Integrated Model (AIM): the case of the iron and steel industry in China. Journal of Cleaner Production. 2014;65:120-30.
[54] Kim K-S, Cho Y-J, Jeong S-J. Simulation of CO2 emission reduction potential of the iron and steel industry using a system dynamics model. International Journal of Precision Engineering and Manufacturing. 2014;15:361-73.

55] Hu R. Analysis and Strategy Research on low carbon production mode of China's iron and steel industry: University of Science and Technology Beijing. 2015.
[56] Lu C. Research on the impact of energy-saving technology and energy structure on carbon emission in China's iron and steel industry: China University of Geosciences, Beijing; 2017.
[57] Norbert R, Kim J, Griffay G. A system dynamics framework for the assessment of resource and energy efficiency in iron and steel plants. Journal of Cleaner Production. 2020;276:123663.
[58] Yao X, Yuan X, Yu S, Lei M. Economic feasibility analysis of carbon capture technology in steelworks based on system dynamics. Journal of Cleaner Production. 2021;322:129046.
[59] Zhu X, Zeng A, Zhong M, Huang J, Qu H. Multiple impacts of environmental regulation on the steel industry in China: A recursive dynamic steel industry chain CGE analysis. Journal of Cleaner Production. 2019;210:490-504.
[60] Nechifor V, Calzadilla A, Bleischwitz R, Winning M, Tian X, Usubiaga A. Steel in a circular economy: Global implications of a green shift in China. World Development. 2020;127:104775.
[61] Ren M, Lu P, Liu X, Hossain MS, Fang Y, Hanaoka T, et al. Decarbonizing China’s iron and steel industry from the supply and demand sides for carbon neutrality. Applied Energy. 2021;298:117209.
[62] Li B-S, Chen YAN, Zhang S, Wu Z, Cofala J, Dai H. CLIMATE AND HEALTH BENEFITS OF PHASING OUT IRON & STEEL PRODUCTION CAPACITY IN CHINA: FINDINGS FROM THE IMED MODEL. Climate Change Economics. 2020;11:2041008.
[63] Li L, Lei Y, He C, Wu S, Chen J. Study on the CO2 emissions embodied in the trade of China’s steel industry: based on the input–output model. Natural Hazards. 2017;86:989-1005.
[64] Zheng X, Wang R, Wood R, Wang C, Hertwich EG. High sensitivity of metal footprint to national GDP in part explained by capital formation. Nature Geoscience. 2018;11:269-73.
[65] Li Z, Dai H, Song J, Sun L, Geng Y, Lu K, et al. Assessment of the carbon emissions reduction potential of China's iron and steel industry based on a simulation analysis. Energy. 2019;183:279-90.
[66] Soares N, Santos P, Gervásio H, Costa JJ, Simões da Silva L. Energy efficiency and thermal performance of lightweight steel-framed (LSF) construction: A review. Renewable and Sustainable Energy Reviews. 2017;78:194-209.
[67] Plocher J, Panesar A. Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures. Materials & Design. 2019;183:108164.
[68] Kawajiri K, Kobayashi M, Sakamoto K. Lightweight materials equal lightweight greenhouse gas emissions?: A historical analysis of greenhouse gases of vehicle material substitution. Journal of Cleaner Production. 2020;253:119805.
[69] China Society of Automotive Engineers(China-SAE). Vehicle lightweight technology roadmap. Technology road map for energy saving and new energy vehicles. Beijing: China Machine Press; 2016. p. 373-435.
[70] Vercammen S, Chalabyan A, Ramsbottom O, Ma J, Tsai C. Tsunami, spring tide, or high tide? The growing importance of steel scrap in China. Mckinsey&Company-Metals and Mining Practice. 2017.
[71] Li Z, Hanaoka T. Development of large-point source emission downscale model by estimating the future capacity distribution of the Chinese iron and steel industry up to 2050.

Resources, Conservation and Recycling. 2020;161:104853.
[72] Ma Wenhuan. ZY, Zhan Haihua, Zhang Yaohui, Chen Yuqian. 2019 iron and steel industry operation status analysis and development trend forecast. China Steel Focus. 2020:25-30.
[73] The State Council of the People's Republic of China. 'Made in China 2025' plan. 2015.
[74] Guo Minxiao YH. Analysis of Greenhouse Gas Emission Reduction Opportunities in China's Steel Industry. Energy of China. 2018;40:35-8.
[75] Lu B, Chen G, Chen D, Yu W. An energy intensity optimization model for production system in iron and steel industry. Applied Thermal Engineering. 2016;100:285-95.
[76] Zhang Q, Wei Z, Ma J, Qiu Z, Du T. Optimization of energy use with CO2 emission reducing in an integrated iron and steel plant. Applied Thermal Engineering. 2019;157:113635.
[77] Ding M. The Establishment and Application of Model System for the Path of China CO2 Emissions Peak Target Beijing: Tsinghua University; 2015.
[78] He K, Wang L. A review of energy use and energy-efficient technologies for the iron and steel industry. Renewable and Sustainable Energy Reviews. 2017;70:1022-39.
[79] United States Environmental Protection Agency(US EPA). Available and Emerging Technologies for Reducing Greenhouse Gas Emissions From the Iron and Steel Industry. North Carolina: US EPA; 2012.
[80] International Energy Agency (IEA). Energy Technology Perspectives 2012. Paris2012.
[81] Wang RQ, Jiang L, Wang YD, Roskilly AP. Energy saving technologies and mass-thermal network optimization for decarbonized iron and steel industry: A review. Journal of Cleaner Production. 2020;274:122997.
[82] Zhang F, Huang K. The role of government in industrial energy conservation in China: Lessons from the iron and steel industry. Energy for Sustainable Development. 2017;39:101-14.
[83] International Energy Agency (IEA). Tracking Industry 2020. Paris, France2020.
[84] International Energy Agency (IEA). Transforming Industry through CCUS. Paris2019.
[85] Birat J. ULCOS II has been shaping up. Retrieved October2009. p. 2010.
[86] Birat J-P, Borlée J, Korthas B, Van der Stel J, Meijer K, Günther C, et al. ULCOS program: a progress report in the Spring of 2008. 3rd International Conference on Process Development in Iron and Steelmaking 2008.
[87] Rootzén J, Johnsson F. Exploring the limits for CO2 emission abatement in the EU power and industry sectors—Awaiting a breakthrough. Energy Policy. 2013;59:443-58.
[88] Fu J-x, Tang G-h, Zhao R-j, Hwang W-s. Carbon Reduction Programs and Key Technologies in Global Steel Industry. Journal of Iron and Steel Research, International. 2014;21:275-81.
[89] Abdul Quader M, Ahmed S, Dawal SZ, Nukman Y. Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO2) Steelmaking (ULCOS) program. Renewable and Sustainable Energy Reviews. 2016;55:537-49.
[90] Meijer K, Denys M, Lasar J, Birat J-P, Still G, Overmaat B. ULCOS: ultra-low CO2 steelmaking. Ironmaking & Steelmaking. 2009;36:249-51.
[91] Karakaya E, Nuur C, Assbring L. Potential transitions in the iron and steel industry in Sweden: Towards a hydrogen-based future? Journal of Cleaner Production. 2018;195:651-63.
[92] Kushnir D, Hansen T, Vogl V, Åhman M. Adopting hydrogen direct reduction for the Swedish steel industry: A technological innovation system (TIS) study. Journal of Cleaner

Production. 2020;242:118185.
[93] Mandova H, Patrizio P, Leduc S, Kjärstad J, Wang C, Wetterlund E, et al. Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage. Journal of Cleaner Production. 2019;218:118-29.
[94] Wijk O, Hyllander G, Sandberg J, Tottie M, Sundelin B, Thorén M, et al. Slutrapport HYBRIT–Hydrogen Breakthrough Ironmaking Technology. Genomförbarhetsstudie Energimyndighetens projektnr. 2018:42684-1.
[95] Luossavaara-Kiirunavaara AB(LKAB), Swedish Steel AB(SSAB), Vattenfall. HYDRID Prestudy release/HYBRID Brochure. 2018.
[96] Simon Kroop. Energy-efficient hydrogen production for today's and future steelmaking. Virtual Forum about Hydrogen @ Mining: Best Practice Examples of Hydrogen Applications. Germany2020.
[97] Salzgitter AG GmbH. S, Sunfire GmbH., et al. Low carbon steel making. 2019.
[98] Tonomura S. Outline of Course 50. Energy Procedia. 2013;37:7160-7.
[99] Hayashi M, Mimura T. Steel Industries in Japan Achieve Most Efficient Energy Cut - off Chemical Absorption Process for Carbon Dioxide Capture from Blast Furnace Gas. Energy Procedia. 2013;37:7134-8.
[100] Watakabe S, Miyagawa K, Matsuzaki S, Inada T, Tomita Y, Saito K, et al. Operation trial of hydrogenous gas injection of COURSE50 project at an experimental blast furnace. ISIJ international. 2013;53:2065-71.
[101] Tonomura S, Kikuchi N, Ishiwata N, Tomisaki S, Tomita Y. Concept and current state of CO 2 ultimate reduction in the steelmaking process (COURSE50) aimed at sustainability in the japanese steel industry. Journal of Sustainable Metallurgy. 2016;2:191-9.
[102] Christopher Manning VFC. Maximizing Iron Unit Yield from Ore to Liquid Steel (Part 2 – DRI physical properties and DRI handling and storage). 2020.
[103] Hyl Technologies S.A. de C.V. ENERGIRON - The Smart Choice. 2020.
[104] Ramakgala C, Danha G. A review of ironmaking by direct reduction processes: Quality requirements and sustainability. Procedia Manufacturing. 2019;35:242-5.
[105] Yilmaz C, Turek T. Modeling and simulation of the use of direct reduced iron in a blast furnace to reduce carbon dioxide emissions. Journal of Cleaner Production. 2017;164:1519-30.
[106] Cameron I, Sukhram M, Lefebvre K, Davenport W. Chapter 44 - Top Charged Direct Reduced Iron. In: Cameron I, Sukhram M, Lefebvre K, Davenport W, editors. Blast Furnace Ironmaking: Elsevier; 2020. p. 409-28.
[107] Voestalpine AG. Deliverable Report D2.8 KPIs to monitor the demonstrations and perform the exploitation tasks. 2017.
[108] Zhang X, Fan J-L, Wei Y-M. Technology roadmap study on carbon capture, utilization and storage in China. Energy Policy. 2013;59:536-50.
[109] Ministry of Science and Technology of the People's Republic of China TACfCsA. Roadmap for carbon capture,utilization and storage technology development in China. 2019. Beijing: Science Press; 2019.
[110] Zhang Q, Li Y, Xu J, Jia G. Carbon element flow analysis and CO2 emission reduction in iron and steel works. Journal of Cleaner Production. 2018;172:709-23.
[111] Lin B, Wang X. Carbon emissions from energy intensive industry in China: Evidence from the iron & steel industry. Renewable and Sustainable Energy Reviews. 2015;47:746-54.

[112] De Ras K, Van de Vijver R, Galvita VV, Marin GB, Van Geem KM. Carbon capture and utilization in the steel industry: challenges and opportunities for chemical engineering. Current Opinion in Chemical Engineering. 2019;26:81-7.
[113] Raj JR, Seetharaman A. Role of waste and performance management in the construction industry. Journal of Environmental Science and Technology. 2013;6:119-29.
[114] Ho MT, Bustamante A, Wiley DE. Comparison of CO2 capture economics for iron and steel mills. International Journal of Greenhouse Gas Control. 2013;19:145-59.
[115] Zongguo W, Zhiyu T, Bai Q, Li J, Zhang Y. Climate and environmental evolution in China: 2021; Chapter 6: Industry. Beijing: Beijing Science Press; 2021.
[116] Peters M, Köhler B, Kuckshinrichs W, Leitner W, Markewitz P, Müller TE. Chemical technologies for exploiting and recycling carbon dioxide into the value chain. ChemSusChem. 2011;4:1216-40.
[117] Han B, Wei G, Zhu R, Wu W, Jiang JJ, Feng C, et al. Utilization of carbon dioxide injection in BOF–RH steelmaking process. Journal of CO2 Utilization. 2019;34:53-62.
[118] Li Z. Investigations on Fundamental Theory of CO2 Applied in Steelmaking Processes: Ph. D. Thesis, University of Science and Technology Beijing, Beijing, China; 2017.
[119] Yi C, Zhu R, Chen BY, Wang CR, Ke JX. Experimental research on reducing the dust of BOF in CO2 and O2 mixed blowing steelmaking process. ISIJ International. 2009;49:1694-9.
[120] Liu Y, Li F, Zhang X, Ji X. Recent progress on electrochemical reduction of CO2 to methanol. Current Opinion in Green and Sustainable Chemistry. 2020;23:10-7.
[121] Li J, Wang L, Cao Y, Zhang C, He P, Li H. Recent advances on the reduction of CO2 to important C2+ oxygenated chemicals and fuels. Chinese Journal of Chemical Engineering. 2018;26:2266-79.
[122] Global CCS Institute. Global Status of CCS 2019, Targeting Climate Change. Australia2020.
[123] International Energy Agency Greenhouse Gas R&D programme(IEA GHG). CCS in energy and climate scenarios. Paris2019.
[124] Gielen D, Boshell F, Saygin D, Bazilian MD, Wagner N, Gorini R. The role of renewable energy in the global energy transformation. Energy Strategy Reviews. 2019;24:38-50.
[125] Gielen D, Saygin D, Taibi E, Birat JP. Renewables-based decarbonization and relocation of iron and steel making: A case study. Journal of Industrial Ecology. 2020.
[126] Otto A, Robinius M, Grube T, Schiebahn S, Praktiknjo A, Stolten D. Power-to-steel: Reducing CO2 through the integration of renewable energy and hydrogen into the German steel industry. Energies. 2017;10:451.
[127] Vogl V, Åhman M, Nilsson LJ. Assessment of hydrogen direct reduction for fossil-free steelmaking. Journal of Cleaner Production. 2018;203:736-45.
[128] Rechberger K, Spanlang A, Sasiain Conde A, Wolfmeir H, Harris C. Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking. steel research international. 2020;91:2000110.
[129] Sarkar S, Bhattacharya R, Roy GG, Sen PK. Modeling MIDREX Based Process Configurations for Energy and Emission Analysis. steel research international. 2018;89:1700248.
[130] Junjie Y. Progress and future of ultra-low CO2 steel making program. China Metallurgy. 2017;27:6-11.

[131] Ping Z, Laijun W, Songzhe C, Jingming X. Progress of nuclear hydrogen production through the iodine–sulfur process in China. Renewable and Sustainable Energy Reviews. 2018;81:1802-12.
[132] Bicer Y, Khalid F. Life cycle environmental impact comparison of solid oxide fuel cells fueled by natural gas, hydrogen, ammonia and methanol for combined heat and power generation. International Journal of Hydrogen Energy. 2018.
[133] Cetinkaya E, Dincer I, Naterer GF. Life cycle assessment of various hydrogen production methods. International Journal of Hydrogen Energy. 2012;37:2071-80.
[134] Hao H, Mu Z, Liu Z, Zhao F. Abating transport GHG emissions by hydrogen fuel cell vehicles: Chances for the developing world. Frontiers in Energy. 2018;12:466-80.
[135] Lee D-Y, Elgowainy A. By-product hydrogen from steam cracking of natural gas liquids (NGLs): Potential for large-scale hydrogen fuel production, life-cycle air emissions reduction, and economic benefit. International Journal of Hydrogen Energy. 2018;43:20143-60.
[136] Lee D-Y, Elgowainy A, Dai Q. Life cycle greenhouse gas emissions of hydrogen fuel production from chlor-alkali processes in the United States. Applied Energy. 2018;217:467-79.
[137] Li G, Cui P, Wang Y, Liu Z, Zhu Z, Yang S. Life cycle energy consumption and GHG emissions of biomass-to-hydrogen process in comparison with coal-to-hydrogen process. Energy. 2019:116588.
[138] Li G, Zhang K, Yang B, Liu F, Weng Y, Liu Z, et al. Life cycle analysis of a coal to hydrogen process based on ash agglomerating fluidized bed gasification. Energy. 2019;174:638-46.
[139] Li J, Ma X, Liu H, Zhang X. Life cycle assessment and economic analysis of methanol production from coke oven gas compared with coal and natural gas routes. Journal of Cleaner Production. 2018;185:299-308.
[140] Li M, Zhang X, Li G. A comparative assessment of battery and fuel cell electric vehicles using a well-to-wheel analysis. Energy. 2016;94:693-704.
[141] Liu X, Yuan Z. Life cycle environmental performance of by-product coke production in China. Journal of Cleaner Production. 2016;112:1292-301.
[142] Mehmeti A, Angelis-Dimakis A, Arampatzis G, McPhail S, Ulgiati S. Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies. Environments. 2018;5:24.
[143] Ozbilen A, Dincer I, Rosen MA. Comparative environmental impact and efficiency assessment of selected hydrogen production methods. Environmental Impact Assessment Review. 2013;42:1-9.
[144] Salkuyeh YK, Saville BA, MacLean HL. Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes. International Journal of Hydrogen Energy. 2018;43:9514-28.
[145] Siddiqui O, Dincer I. A well to pump life cycle environmental impact assessment of some hydrogen production routes. International Journal of Hydrogen Energy. 2019;44:5773-86.
[146] Suleman F, Dincer I, Agelin-Chaab M. Comparative impact assessment study of various hydrogen production methods in terms of emissions. International Journal of Hydrogen Energy. 2016;41:8364-75.
[147] Valente A, Iribarren D, Dufour J. Harmonised life-cycle global warming impact of renewable hydrogen. Journal of Cleaner Production. 2017;149:762-72.

[148] Valente A, Iribarren D, Dufour J. Harmonising the cumulative energy demand of renewable hydrogen for robust comparative life-cycle studies. Journal of Cleaner Production. 2018;175:384-93.
[149] Wang Z, Li L, Zhang G. Life cycle greenhouse gas assessment of hydrogen production via chemical looping combustion thermally coupled steam reforming. Journal of Cleaner Production. 2018;179:335-46.
[150] Yazdanie M, Noembrini F, Heinen S, Espinel A, Boulouchos K. Well-to-wheel costs, primary energy demand, and greenhouse gas emissions for the production and operation of conventional and alternative vehicles. Transportation Research Part D: Transport and Environment. 2016;48:63-84.
[151] Zhao G, Pedersen AS. Life Cycle Assessment of Hydrogen Production and Consumption in an Isolated Territory. Procedia CIRP. 2018;69:529-33.
[152] Ren L, Zhou S, Ou X. Life-cycle energy consumption and greenhouse-gas emissions of hydrogen supply chains for fuel-cell vehicles in China. Energy. 2020;209:118482.
[153] Wind Information. Wind Economic Database. In: Wind, editor.2020.
[154] National Bureau of statistics of the People's Republic of China(NBSPRC). National railway freight volume by cargo category. 2019.
[155] Farjana SH, Huda N, Parvez Mahmud MA, Saidur R. A review on the impact of mining and mineral processing industries through life cycle assessment. Journal of Cleaner Production. 2019;231:1200-17.
[156] Ferreira H, Leite MGP. A Life Cycle Assessment study of iron ore mining. Journal of Cleaner Production. 2015;108:1081-91.
[157] Gan Y, Griffin WM. Analysis of life-cycle GHG emissions for iron ore mining and processing in China—Uncertainty and trends. Elsevier Ltd; 2018. p. 90-6.
[158] Jha G, Soren S, Mehta KD. Life cycle assessment of sintering process for carbon footprint and cost reduction: A comparative study for coke and biomass-derived sintering process. Elsevier Ltd; 2020. p. 120889.
[159] Lv W, Sun Z, Su Z. Life cycle energy consumption and greenhouse gas emissions of iron pelletizing process in China, a case study. Elsevier Ltd; 2019. p. 1314-21.
[160] Chisalita D-A, Petrescu L, Cobden P, van Dijk HAJE, Cormos A-M, Cormos C-C. Assessing the environmental impact of an integrated steel mill with post-combustion CO2 capture and storage using the LCA methodology. Journal of Cleaner Production. 2019;211:1015-25.
[161] Huang Z, Ding X, Sun H, Liu S. Identification of main influencing factors of life cycle CO2 emissions from the integrated steelworks using sensitivity analysis. Journal of Cleaner Production. 2010;18:1052-8.
[162] Liang T, Wang S, Lu C, Jiang N, Long W, Zhang M, et al. Environmental impact evaluation of an iron and steel plant in China: Normalized data and direct/indirect contribution. Elsevier Ltd; 2020. p. 121697.
[163] Olmez GM, Dilek FB, Karanfil T, Yetis U. The environmental impacts of iron and steel industry: a life cycle assessment study. Journal of Cleaner Production. 2016;130:195-201.
[164] Tong Y, Cai J, Zhang Q, Gao C, Wang L, Li P, et al. Life cycle water use and wastewater discharge of steel production based on material-energy-water flows: A case study in China. Elsevier Ltd; 2019. p. 118410.

[165] Verones F, Bare J, Bulle C, Frischknecht R, Hauschild M, Hellweg S, et al. LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. Journal of Cleaner Production. 2017;161:957-67.
[166] Chenkai Z. Potential Analysis And Synergy Approaches of Energy Saving and Pollution Reduction: Case In lron Industry. Beijing: Tsinghua University; 2015.
[167] Boya Z. Life Cycle Assessment of Energy Use, Carbon Emissions and Cost Benefit of Electric Vehicles. Beijing: Tsinghua University; 2016.
[168] Tianduo P. Analysis on Energy Consumption, GHG Emissions and Key Mineral Resource Demand for Electric Vehicles in China. Beijing: Tsinghua University; 2019.
[169] Ou X, Zhang X, Chang S. Alternative fuel buses currently in use in China: Life-cycle fossil energy use, GHG emissions and policy recommendations. Energy Policy. 2010;38:406-18.
[170] Ou X, Xiaoyu Y, Zhang X. Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China. Applied Energy. 2011;88:289-97.
[171] Ou X, Yan X, Zhang X, Liu Z. Life-cycle analysis on energy consumption and GHG emission intensities of alternative vehicle fuels in China. Applied Energy. 2012;90:218-24.
[172] Li X, Ou X, Zhang X, Zhang Q, Zhang X. Life-cycle fossil energy consumption and greenhouse gas emission intensity of dominant secondary energy pathways of China in 2010. Energy. 2013;50:15-23.
[173] Peng T, Ou X, Yan X. Development and application of an electric vehicles life-cycle energy consumption and greenhouse gas emissions analysis model. Chemical Engineering Research and Design. 2018;131:699-708.
[174] Ministry of Industry and Information Technology (MIIT). Admittance conditions of scrap steel processing industry. 2012.
[175] Kuramochi T. Assessment of midterm CO2 emissions reduction potential in the iron and steel industry: a case of Japan. Journal of Cleaner Production. 2016;132:81-97.
[176] Liu Y, Li H, Huang S, An H, Santagata R, Ulgiati S. Environmental and economic-related impact assessment of iron and steel production. A call for shared responsibility in global trade. Journal of Cleaner Production. 2020;269:122239.
[177] He X, Kim HC, Wallington TJ, Zhang S, Shen W, De Kleine R, et al. Cradle-to-gate greenhouse gas (GHG) burdens for aluminum and steel production and cradle-to-grave GHG benefits of vehicle lightweighting in China. Resources, Conservation and Recycling. 2020;152:104497.
[178] The World Steel Association(WSA). Sustainability indicators: data 2003 to 2018 and participation details. Brussels, Belgium2020.
[179] The World Steel Association(WSA). LCI methodology report. Brussels, Belgium2017.
[180] Zou P, Chen Q, Yu Y, Xia Q, Kang C. Electricity markets evolution with the changing generation mix: An empirical analysis based on China 2050 High Renewable Energy Penetration Roadmap. Applied Energy. 2017;185:56-67.
[181] Energy Research Institute of National Development and Reform Commission. China 2050 High Renewable Energy Penetration Scenario and Roadmap Study. Beijing;2015.
[182] Shen W, Han WJ, Wallington TJ, Winkler SL. China Electricity Generation Greenhouse Gas Emission Intensity in 2030: Implications for Electric Vehicles. ENVIRONMENTAL SCIENCE & TECHNOLOGY. 2019;53:6063-72.

[183] China Hydrogen Alliance. White Paper on China's Hydrogen Energy and Fuel Cell Industry(2019, 2020). Beijing, China2019.
[184] International Energy Agency. An energy sector roadmap to carbon neutrality in China. 2021.
[185] International Energy Agency. Iron and Steel Technology Roadmap. 2021.
[186] Yang Y, Wang G, Lin L, Zhang S. Analysis of hydrogen production potential based on resources situation in China. E3S Web of Conferences: EDP Sciences; 2019. p. 03021.

Energy **D**emand changes **I**nduced by **T**echnological and **S**ocial innovations (EDITS)

EDIT Project Report

Demographic Changes and Energy Consumption Behaviors in Korea

February 24, 2022

Tae Yong Jung

The Korean Society of Climate Change Research

TABLE OF CONTENT

1. INTRODUCTION 2
2. AN ANALYSIS OF RESIDENTIAL ELECTRICITY DEMAND WITH DEMOGRAPHIC CHANGE IN KOREA 4
3. AN ANALYSIS ON RESIDENTIAL ENERGY DEMAND IN KOREA.............. 24
4. IMPACT OF LOW ENERGY DEMAND ON SDGS IN KOREA..................... 33

REFERENCE 49

1. INTRODUCTION

- EDITS Background

Levels and structure of energy and resource demands are increasingly recognized as a key critical determinant of feasibility, timing, and costs of climate mitigation actions and their SDG synergies and tradeoffs. *Ceteris paribus*, the higher the demand, the earlier, the more stringent, and the more costly climate mitigation will have to be, that all could therefore raise significant tradeoffs with other SDG objectives. Conversely, lower demands increase the temporal flexibility of climate mitigation and reduce the stringency and costs of mitigation actions, thus also reducing the risks of SDG tradeoffs.

It is important to emphasize that energy and resource demands themselves are intermediary variables. By themselves, physical resource demands are not directly enhancing human welfare and wellbeing (or utility). Rather it is the *services and amenities* that the use of energy and other resources provides; that is the ultimate social goal of resource consumption. The efficiency of resource use and the efficacy of alternative service provision models thus move into the center stage of climate mitigation from a demand or end-use perspective.

Because of the high heterogeneity of consumers and the multitude of demand types (food, shelter, mobility, communication, etc.), the theoretical understanding and modeling of “demand” (outside aggregated simplistic formulation) remains limited and fragmented, as are resulting capabilities to propose and to assess demand-side policy interventions from the twin angle of climate mitigation as well as of promoting the SDGs.

The Japanese government developed a “long-term strategy as a growth strategy based on the Paris Agreement” in June 2019 and set a goal to achieve decarbonization as early as possible in the second half of this century.

In October 2018, the Intergovernmental Panel on Climate Change (IPCC) approved and published a 1.5 °C special report, including low energy demand (LED) scenarios with accompanying technological progress and social changes, such as AI, which was mainly developed by the International Institute for Applied Systems Analysis (IIASA), was presented and attracted attention. However, at present, the quantitative and comprehensive analysis has not been sufficiently performed.

At the IPCC, the sixth evaluation cycle is in full swing, and it is required to provide the latest scientific knowledge on climate change. Therefore, in order not only to realize a virtuous cycle between the environment and growth but also to actively contribute to the demands of the IPCC, conducting the quantitative and comprehensive analysis of changes in energy demand led by technological innovation and social change is extremely important.

- EDITS Objective

In this project, while considering the latest scientific knowledge and global trends, quantitative and comprehensive analysis and evaluation will be conducted by competitive models based on the following topics:
(1) Technological innovation on the energy demand side
(2) Social changes resulting from (1)
(3) Further impact on CO2 emission reduction
(4) A comparative evaluation of the scenario with major global research institutions.

Through these efforts, in addition to mainstreaming the positioning of major climate change scenarios in the international research community, inputting them into the IPCC report is another objective of this project.

- EDITS Project Team (Korea)
  - Tae Yong Jung (Project Manager, Professor, Yonsei University)
  - Yong Gun Kim (Senior Fellow, Korea Environment Institute)
  - Chan Park (Professor, University of Seoul)
  - Jin Han Park (Fellow, Korea Environment Institute)
  - Jongwoo Moon (Instructor, Yonsei University)

2. AN ANALYSIS ON RESIDENTIAL ELECTRICITY DEMAND WITH DEMOGRAPHIC CHANGE IN KOREA[1]

2.1 Introduction

Understanding the demographic structure, such as population size and age and gender composition, and household characteristics, such as household size, has become an important topic for analyzing the energy demands in many countries. Especially, Korea is a representative case of experiencing the rapid demographic and household structure changes led by the low fertility rates and longer life expectancies. These changes would affect energy demands and greenhouse gas emission trends via various channels, including behavioral changes.

The Korean society is rapidly changing towards an aging society and is expected to be one of the most aged societies in the world by 2067 (Statistics Korea 2019b). In addition to the longer life expectancy, a very low birth rate in recent years, lower than one, further accelerates the socio-demographic transformation of society. This change is expected to lead the share of the population aged 65 or older to exceed 45% of the population in the future. (See Figure 2-1.)

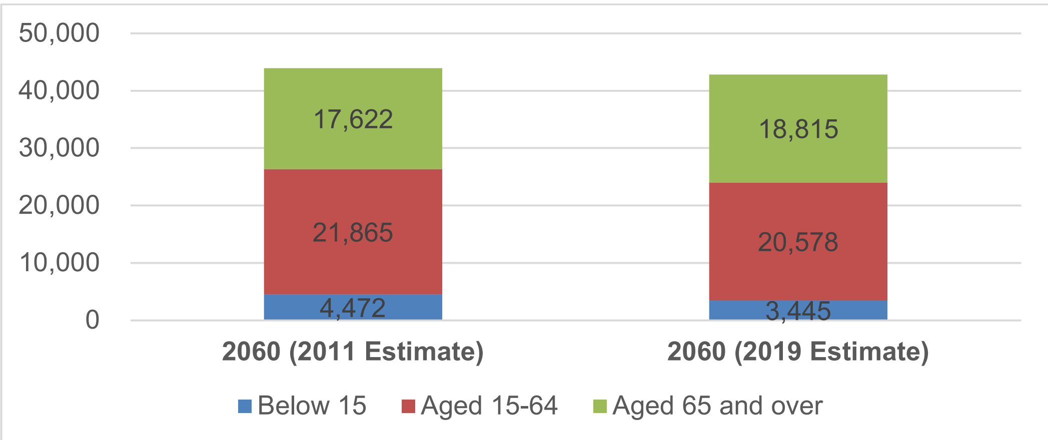


Figure 2-1 Population Prospects (2011 estimate vs. 2019 estimate)

Source: (Statistics Korea 2011, 2019b)

---

[1] This chapter includes the updated results from Moon, J. 2022. An Analysis on Sustainable Electricity Supply and Demand in Korea with Application of Machine Learning Techniques (Doctoral dissertation). Yonsei University: Seoul, Republic of Korea

Moreover, there is a clear trend of smaller households, including single-member households, in Korea. The household prospects expected the share of single-person households to reach 37% in 2047 from 28.5% in 2017. Also, single-member or two-member households are expected to exceed 70% of the entire households in 2047. These clear trends of an aging society and smaller households are closely linked to energy consumption patterns and behaviors. The study examines how demographic and household characteristics affect the residential electricity consumption of Korea. (See Figure 2-2.)

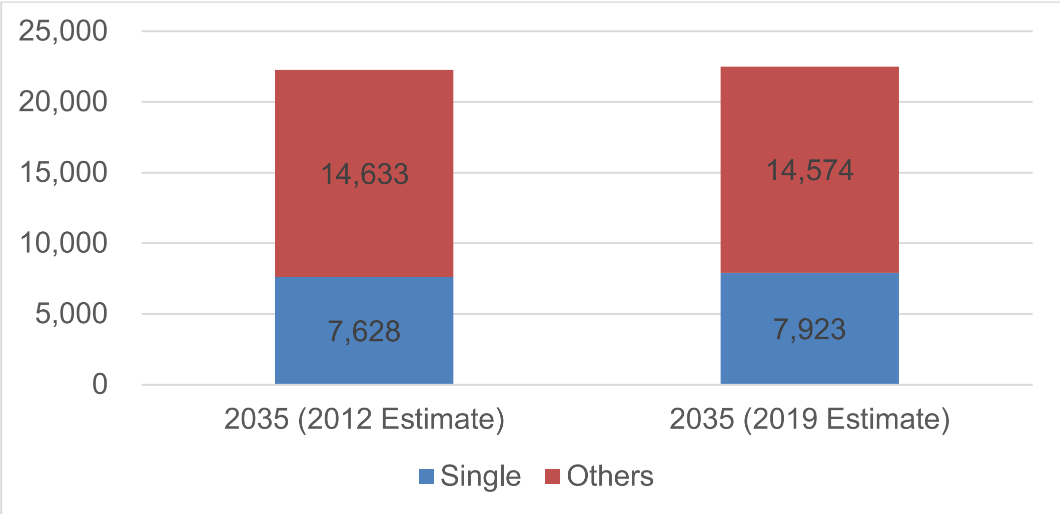


Figure 1-2 Household Prospects (2012 estimate vs. 2019 estimate)

Source: (Statistics Korea 2012, 2019a)

	Year	Population in 2060 (thousand)	Population aged 15-64 in 2060 (thousand)	Share (%)	Population aged 65 or more in 2060 (thousand)	Share (%)
Population Prospects	2011	43,959	21,865	49.7	17,622	40.1
Population Prospects	2019	42,838	20,578	48.0	18,815	43.9
Source: (Statistics Korea 2011, 2019b)						

Table 2-1 Comparison of Population Prospects (2011 vs. 2019)

	Year	Total number of households in 2035 (thousand)	Total number of single-member households in 2030 (thousand)	Share of single-member households (%)
Household Prospects	2012	22,261	7,628	34.27
Household Prospects	2019	22,497	7,923	35.22
Source: (Statistics Korea 2012, 2019a)				

Table 1-2 Comparison of Household Prospects

Figure 2-3 shows the comparison of the demographic structures from the United Nations in 2010 and 2019 (United Nations Department of Economic and Social Affairs, 2010, 2019). This figure shows that Korean society is likely to reach an aged society earlier. When comparing the share of the aged population of two prospects, the 2019 population prospects expected that the share of the aged population aged 65 or older would reach over 38% in 2050, which is much higher than 32.8% from the 2010 population prospects.

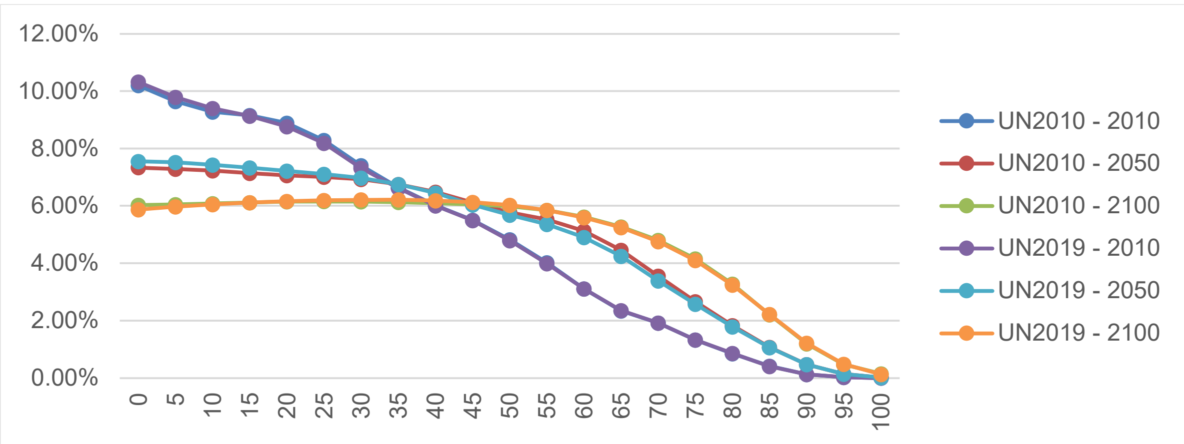


Figure 2-2 Demographic Structure (UN 2010 and UN 2019 Comparison)

Source: (United Nations Department of Economic and Social Affairs 2010, 2019)

The study analyzed the social, economic, and weather data of 16 municipalities in Korea at the local municipal level to examine the effects of the socio-economic drivers on residential electricity consumption. Considering the local socio-demographic and climate factors of municipalities with different characteristics would allow understanding the drivers of the residential electricity consumption in Korea. The study used the balanced panel data of 16 municipalities in Korea over the period 2007-2019, and data is collected from e-local indicators from Statistics Korea, Korea National Data Center, and Korea Electric Power Corporation's Electric Data Portal System (Statistics Korea 2021; Korea National Climate Data Center 2021; Korea Electric Power Corporation 2021).

Variable Name	**Description**		Mean	Std
Residential Electricity consumption (per capita)	Electricity consumption per capita in the residential sector		0.1883	0.0771
Residential electricity price	Residential Electricity Price adjusted by regional CPI	Economic	4.8030	0.1004
Personal Income	Residential income per capita adjusted by regional CPI	Economic	9.6988	0.1245
Share over aged 65	Share of population aged 65 or older	Demographic	13.2385	3.5977
Aging Index	Population aged 65 or older / Population aged 0~14	Demographic	0.8913	0.3250
HDD	Heating Degree Days (Below 18 degrees Celsius)	Weather	7.7371	0.1948
CDD	Cooling Degree Days (Over 24 degrees Celsius)	Weather	4.9989	0.4278
Household member	Number of members in a household	Household	0.9951	0.0632
APT_Share	Share of Apartment	Housing	0.5533	0.1161
Gwang	Metropolitan City (Yes = 1, Otherwise =0)	Geographic	0.4375	0.4973
Interact	Gwang * Share over aged 65		4.7207	5.6156

Table 2-2 Descriptive statistics of variables

Panel regression models, particularly fixed effects and random effects models, are established to examine the drivers of the residential electricity consumption, and the Hausman test is used to select the appropriate model. Levin-Liu-Chu test is also applied and found that the variables do not contain the unit root at the 5% significance level.

<u>Panel Regression: Fixed Effects and Random Effects</u>

$$
\begin{aligned}
Res\_Elec\_PC_t &= \beta_0 + \beta_1 Pers\_inc\_PC_t + \beta_2 Elec\_Price_t + \beta_3 Pop\_over\_65_t \\
&+ \beta_4 HDD_t + \beta_5 CDD_t + \beta_6 Population\ per\ household_t \\
&+ \beta_7 APT\_Share_t + \beta_8 GWANG_t + \beta_9 Interact_t + e_t
\end{aligned}
$$

‘Gwang' dummy variable, which is time-invariant, is dropped in the fixed-effect model

The results of the fixed and random effect models show similar results. The study conducted the Hausman test to choose the appropriate model, and the test result indicates that the null hypothesis that the difference between the coefficients is not systematic is strictly rejected at the 1% significance level. According to the Hausman test, the fixed-effect model is considered to analyze the drivers of residential electricity consumption. Like other literature, there is a statistically significant negative price elasticity on residential electricity consumption but a statistically significant positive income elasticity on residential electricity consumption. The result indicates that a one percent increase in the real residential electricity price is associated with an approximately 0.09% decrease in the residential electricity consumption per capita, ceteris paribus. Also, the result indicates that a one percent increase in the real personal income per capita is associated with an approximately 0.206% increase in the residential electricity consumption per capita, ceteris paribus. When comparing the income and price elasticity, the income elasticity is larger than the price elasticity. A possible explanation is that electricity is a necessary good and an important input for our living and economy, and the income level would affect the number, type, and size of appliances and electronic devices used. It is reasonable to have inelastic price elasticity but more elastic income elasticity.

For the aging factor, the panel regression result suggests that the share of the population aged over 65 has a positive and statistically significant effect on residential electricity consumption. It indicates that a one percentage point increase of population aged over 65 is associated with an approximately 1.2% increase in residential electricity consumption. This result indicates that the elderly population in Korea tends to consume more electricity at home, possibly due to more hours staying indoors, and suggests that the aging factor could be a significant factor for analyzing the residential electricity consumption.

The coefficient of the number of household members indicates the average number of people per household shows the effects of increasing single households (or decreasing household size) on electricity consumption per capita. As stated above, the household prospects suggest a trend of increasing single- or two-member households in Korea. From the panel regression, a one percent decrease of population per household (reduced average number of members in a household) is associated with a 0.185% increase in residential electricity consumption per capita, ceteris paribus, at the 5% significance level. This result indicates that the electricity consumption per capita is expected to increase if the number of household members decreases, which is the current situation in Korea. For heating degree-days below 18 degrees Celsius and cooling degree days over 24 degrees Celsius, both coefficients show positive effects on residential electricity consumption per capita and are statistically significant at the 1% significance level. This result is reasonable that people tend to use more use of air conditioners and cooling devices in summer and use heating devices during the cold weather. In addition, it is likely that people spend more time indoors and do more indoor activities on hot or cold days. Lastly, the share of apartments, which is the housing characteristics, indicates that a one percentage point increase in the share of apartments leads to a 0.83 percent increase in the residential electricity consumption, ceteris paribus. People living in apartments consume more electricity than those living in other types of housing. A potential reason for this is that people living in apartments may have higher wealth than others because the value of the apartment is typically higher than other types of housing. (See Table 2-4.)

Variable	lRes_Elec_Capita (Fixed Effect)	lRes_Elec_Capita (Random Effect)
Electricity Price (Regional CPI)	-0.0949*** (0.0342)	-0.1702*** (0.0362)
Income per capita (Regional CPI)	0.2057*** (0.0568)	0.2550*** (0.0416)
Share_Over_65_Pop	0.0120*** (0.0032)	0.0085*** (0.0023)
HDD	0.1929*** (0.0285)	0.1428*** (0.0217)
CDD	0.0189*** (0.0049)	0.0246*** (0.0048)
lpop_h	-0.1845** (0.0937)	-0.1152 (0.1000)
APT_Share_case	0.8304*** (0.1212)	0.2960*** (0.0628)
Gwang		0.0669*** (0.0254)
Interact	-0.0078*** (0.0016)	-0.0049*** (0.0016)
Constant	-3.3360*** (0.7239)	-2.8631*** (0.5842)
Observation	208	208
Number of Groups	16	16
R-squared (Within)	0.9347	0.8763
(Between)	0.4093	0.5811
(Overall)	0.5575	0.7529
* p<0.1; ** p<0.05; *** p<0.01		

Table 2-4 Estimation Result: Panel Model I

Variable	Coefficients			
	(b) fe1	(B) re1	(b-B) Difference	S.E.
Electricity Price (Regional CPI)	-0.0949	-0.1702	0.0753	.
Income per capita (Regional CPI)	0.2057	0.2550	-0.0492	0.0388
Share_Over_65_Pop	0.0120	0.0085	0.0035	0.0022
HDD	0.1929	0.1428	0.0500	0.0184
CDD	0.0189	0.0246	-0.0058	0.0005
lpop_h	-0.1845	-0.1152	-0.0693	.
APT_Share_case	0.8304	0.2960	0.5344	0.1037
Interact	-0.0078	-0.0049	-0.0030	.
H_0: Difference in coefficients not systematic Chi-square = 67.63 Probability>Chi-square = 0.0000				

Table 2-3 Hausman Test

The study found that the income elasticity is higher than the price elasticity, so the income growth is likely to lead to the increase of residential electricity consumption per capita even though the electricity price increases in the future. The study also found that the heating degree days below 18 degrees Celsius and cooling degree days over 24 degrees Celsius affect the residential electricity consumption per capita positively. Increased use of cooling devices, such as air conditioners, or heating devices, such as electronic heaters, can be attributed to this result, and individuals are more likely to spend more time at home and do indoor activities during hot or cold weather. As the impacts of climate change become more significant, weather patterns are likely to change, resulting in more extreme weather events and more cooling degree days or heating degree days. This result restates that climate change and weather conditions would affect the residential electricity consumption per capita in the future. According to various global and regional climate models (Korea Meteorological Administration 2020), in general, extreme weather indices related to high temperatures, such as heatwave days, tropical nights, and summer days, tend to increase, but those related to low temperatures, such as cold wave days, ice days, and frost days, tend to decrease in the short-term. In the long-term, the forecast suggests that the average temperature would increase about 2.9 ~ 4.7 degrees Celsius in accordance with RCP scenarios, this long-term trend would affect the residential electricity consumption per capita in mixed directions that the increasing cooling degree days tend to increase the residential electricity consumption, but the decreasing heating degree days tend to decrease the residential electricity consumption. Also, these changes are likely to change the electricity load patterns, which have not been considered in this analysis.

The important key messages of the study are the demographic and household variables, 'share of the population aged over 65', 'aging index,' and 'number of household members' have statistically significant effects on the residential electricity consumption per capita. The aging variables have positive effects on the residential electricity consumption per capita, while the size of a household has negative effects on the residential electricity consumption per capita. Considering the clear trends of household and population prospects of Korea, the result of the study provides some implications. The population prospects in the year 2011 and the year 2019 (Statistics Korea 2011, 2019b) show that the pace of an aging society is expected to accelerate, and the population would decrease further in the future. As the future population reaches the peak and starts to decrease, the electricity demand would also follow a similar pathway. However, the result of the study suggests that aging would affect residential electricity consumption in a positive way.

Moreover, the household prospects in the year 2012 and year 2019 (Statistics Korea 2012, 2019a) suggest that the total number of single-member households would increase, and its share would reach over 35% in the year 2035. Though the Korean population is expected to reach the peak earlier and start to decrease between 2030 and 2035, the prospects of the number of households in 2035 are increased from 22,261 thousand (Statistics Korea 2012) to 22,497 thousand (Statistics Korea 2019a). This indicates that the household structure of Korea is likely to change towards a smaller number of members in a household. The study indicated that the household variable, 'the number of household members' has a statistically negative effect on the residential electricity consumption per capita. In other words, the increasing trends of single-member households and the smaller number of members in a household would affect the residential electricity consumption in a positive way. This result may lead to the following consequences on residential electricity consumption. When the population size reaches a peak and starts to decrease in the future, the decrease in electricity consumption would be less dramatic compared to the population trends due to the positive effects of aging and household structure on residential electricity consumption.

In addition, the interaction term of the study implies the living conditions of the elderly people may affect residential electricity consumption. The study found that the residential electricity consumption per capita is higher for the elderly people living in provinces. A possible explanation is that metropolitan cities tend to have various and well-organized social service facilities and social infrastructure, so elderly people can enjoy more outdoor activities and use less residential electricity. This result implies that the regional difference in the trends of aging society would affect the residential electricity consumption of Korea in the future.

This study can provide additional implications to the findings from (Jung, Kim, and Moon 2021). (Jung, Kim, and Moon 2021) projected the future GDP and CO_2 emissions by establishing a CGE model with UN population prospects from 2010 and 2019 and labor force participation rate. Figure 2-4 shows the result of (Jung, Kim, and Moon 2021) visually. The key finding of the study is that low fertility and an aging population lead to a continuous and further decrease of the Korean population in the future under the UN 2019 Scenario. The increase of the labor participation rates of the economically active age group (aged over 20) would lead to a decrease in GDP from the mid-2040s, which is much later and relatively moderate compared to the decrease in the Korean population. Also, CO_2 emissions of Korea are expected to decrease near 2050 as economic activity reduces. The increase in the labor participation rate leads to a relatively gradual decreasing trend of GDP and CO_2 emissions compared to that of the future population. (Jung, Kim, and Moon 2021) approaches the demographic component, especially the aging aspect, from the labor supply and economic activity side. In addition, the result of the study can provide implications from the energy demand side. The demographic and household variables in this study indicate that the recent trend of the Korean society towards aging society and the smaller households would lead to an increase in the residential electricity consumption per capita. It means that the decrease in the absolute number of populations would lead to a reduction in energy and electricity demands in the future; however, the decreasing trends of the residential electricity consumption are likely to be gradual compared to that of the Korean population. Furthermore, the decreasing trends of the future CO_2 emissions of Korea, led by the decrease of the residential electricity consumption, would be gradual compared to the decreasing trends of the population in the future.

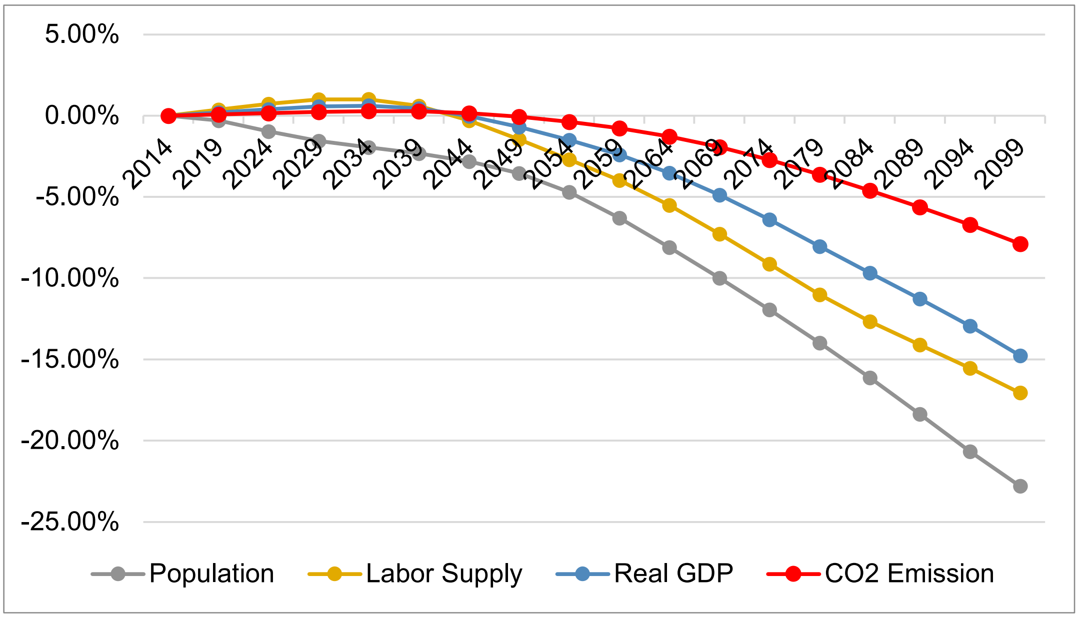


Figure 2-4 Comparison between UN 2019 Mid Scenario vs. UN 2010 Mid Scenarios (baseline): Percentage change of key results
Source: (T.Y. Jung, Kim, and Moon 2021)

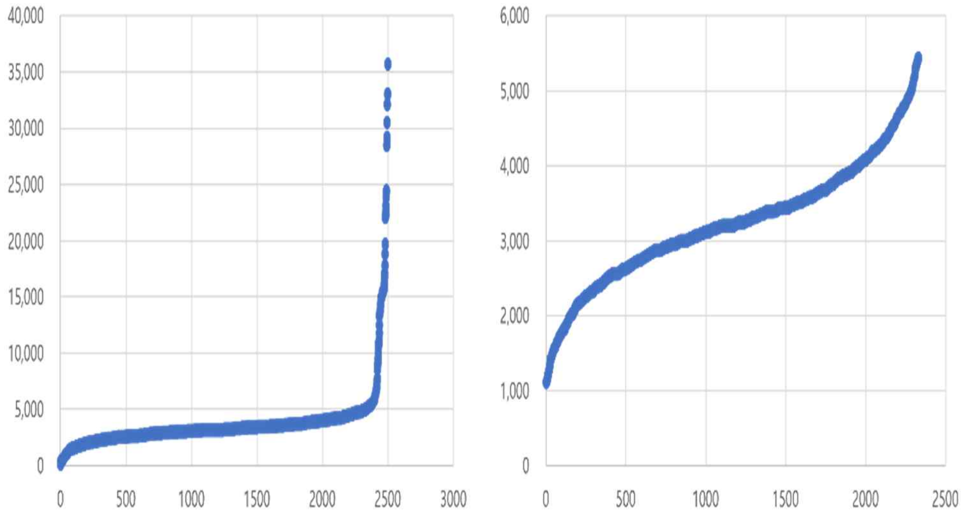
The study further examined the impacts of demographic factors on residential electricity consumption at a micro-level. Understanding human activities and behaviors is a crucial component for understanding electricity demand, but the aggregated, macro-level data have some limitations to identify it. Typically, survey data are widely used to understand human behaviors. It provides a wide range of questionnaires to individuals and households and collects information of interest. In Korea, a few energy surveys are conducted, including Energy Consumption Survey (every three years) and Household Energy Standing Survey (HESS) (every year).

In this analysis, Household Energy Standing Survey (HESS) from Korea Energy Economics Institute (Korea Energy Economics Institute 2019) is considered. This survey is conducted every year to survey electricity consumption, household information, including household members, age of members, and income level, and energy consumption information, including the number of appliances, of 2,520 households in Korea. This panel survey provides a wide range of information on the composition of the household members, the usage patterns of the home appliances, the key features of housing, and the monthly use of various energy sources, including electricity and city gas. This study focuses on the electricity consumption of households, and the panel survey provides many categorical and numerical variables.

The study includes heating degrees days (under 18 degrees Celsius) and cooling degrees days (over 24 degrees Celsius) to consider the impacts of weather conditions and regional differences on residential electricity consumption (Korea National Climate Data Center 2021). Out of 2,520 household information, the study removed households with missing information on electricity consumption and household information from the dataset and used 2,499 households information.

The survey data provides numerical monthly electricity consumption of each household, but several variables that can be potentially considered as independent variables are categorical or dummy variables. Therefore, this study decided to convert the dependent variable from numerical to categorical variable and set a classification-type research question. This would also allow using various machine learning methods, which have strength in classifications. For applying appropriate machine learning techniques, a few preprocessing processes have been applied to the dataset. First, the study aggregated the monthly electricity consumption information and created the dependent variables as the annual electricity consumption. The study used k-means clustering to classify the groups of annual electricity consumption. Also, the study calculated the discomfort days and the heating degrees days by using the temperature information of each province from Korea Statistics. In addition, the study selected demographic variables and key appliances, such as television, computer, air conditioner, refrigerator, washing machine, cooking machine, tv set-top box, and air purifier.

Figure 2-5 shows that the dataset includes outliers of households consuming an extremely small or large amount of electricity annually. The purpose of the study is to understand the characteristics of household electricity consumption, so the study decided to remove the outliers by applying the Interquartile range (IQR) method. This method finds the IQR (the third Quantile of the dataset – the first Quantile of the dataset) and sets lower and upper bounds as (Q1 – 1.5 * IQR) and (Q3 + 1.5 IQR), respectively. By applying the IQR method, for the yearly electricity consumption, 168 outliers are detected and removed from the dataset. After treating outliers, the range of the annual electricity consumption of households became [1,110 kWh ~ 5,434 kWh], which is equivalent to [92.5 kWh ~ 452.83 kWh] per month.



	Observation	Minimum	Maximum	Mean
Original	2,499	135	35,687	3,694.34
Outlier Removal	2,331	1,110	5,434	3,236.223

Figure 2-5 Comparison of annual household electricity consumption (before and after outlier removal) (kWh)

In terms of category, the study used the elbow method and the Silhouette clustering method to find the optimal number of clusters and applied k-means classification methods to classify the dependent variables. The study uses a k-means clustering algorithm to classify and find the clusters (subgroups) of the electricity consumption of households. The Elbow method and Silhouette coefficient are considered to find the appropriate number of clusters classifying 2,331 households in the sample. Both methods suggest the optimal number of k as 3.

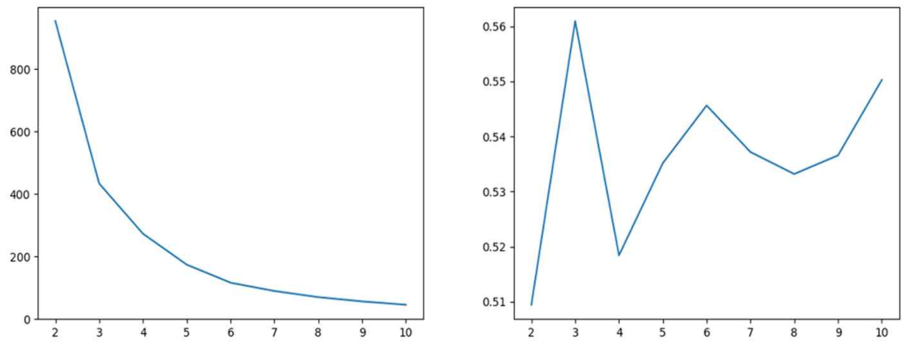


Figure 2-3 Elbow method (left); Silhouette coefficient (right)

For annual electricity consumption, the ranges of electricity consumption of each household group determined by the k-means clustering algorithm and the number of samples in each group are shown below. The range of 2,730 kWh and 3,796 kWh (227.5 kWh ~ 316.33 kWh per month) contains more than half of the household samples.

Classification	Group	Min (kwh)	Max (kwh)	Observations
K-means = 3	1	1,110	2,729	569
	2	3,799	5,434	514
	3	2,730	3,796	1,248

Table 2-6 k-means clustering

The study used Random Forest classification and decision tree classification to classify the annual residential electricity consumption in Korea. To evaluate the classification results of the models, Accuracy, Recall, and F1 Score are mainly considered.

$$Accuracy = \frac{True\ Positive + True\ Negative}{True\ Positive + True\ Negative + False\ Positive + False\ Negative}$$

$$Recall = \frac{True\ Positive}{True\ Positive + False\ Negative}$$

$$Precision = \frac{True\ Positive}{True\ Positive + False\ Positive}$$

$$F1\ Score = 2 * \frac{Precision * Recall}{Precision + Recall}$$

In general, GridSearchCV is applied to find the optimal hyperparameter, and the models are optimized by using 70% of the dataset. The remaining 30% of the dataset is used to test the optimized models. All independent variables are considered in this analysis. First, the annual electricity consumption is classified into three groups by using k-means clustering. Randomized Grid Search is applied to find the optimal parameters (number of estimators, “minimum number of samples required to split an internal node,” “minimum number of samples required to be at a leaf node,” “maximum depth of the tree,” and “number of features considered for the split”). The Search found the optimal hyperparameters as the number of estimators as 410, the minimum number of samples to split an internal node as 8, the minimum number of samples to be at a leaf node as 2, the number of features to consider when searching the best split as the square root of the number of features [sqrt(n_features)], the maximum depth of the tree as 72.

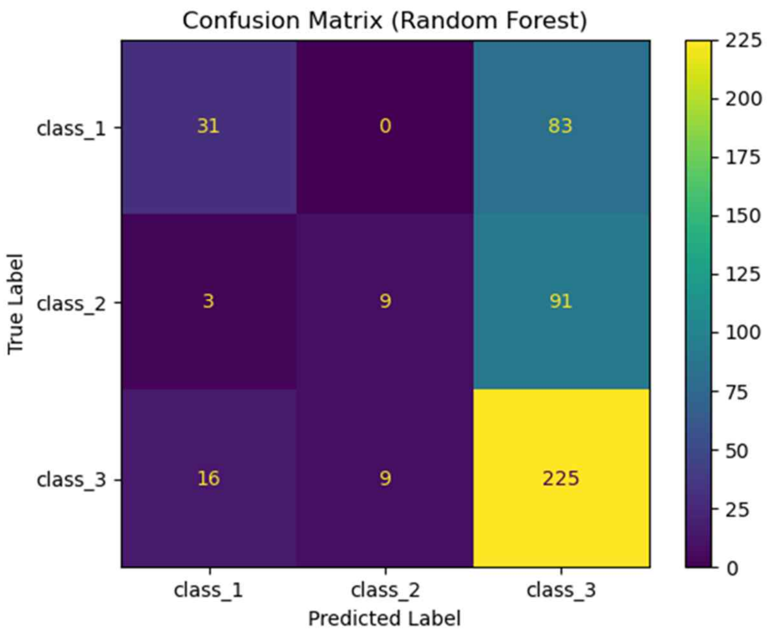


Figure 2-7. Confusion Matrix (Electricity Consumption)

	Precision	Recall	F1 Score	Support
1	0.62	0.27	0.38	114
2	0.50	0.09	0.15	103
3	0.56	0.90	0.69	250
Accuracy			0.57	467
Macro Average	0.56	0.42	0.41	

Weighted Average	0.56	0.57	0.50	

Table 2-7 Classification Report (Group of 3)

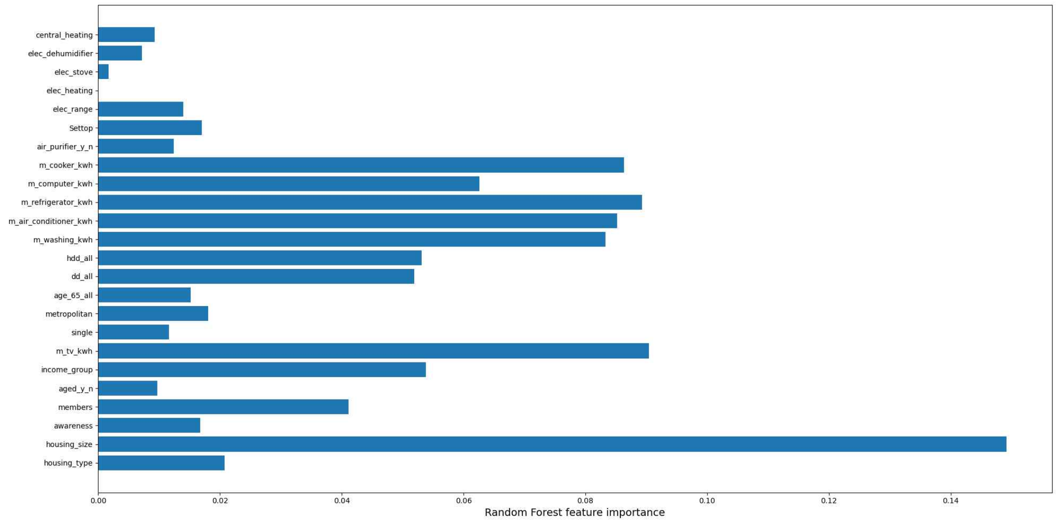


Figure 2-8. Random Forest - Feature Importance

For the case of the group of three, the accuracy and F1 Score (weighted average) of the classification are 0.57 and 0.50, respectively, and the classification result of the Random Forest Classifier indicates many data points in the test set are classified as Group 3, same as the Support Vector Classification. Compared to the Support Vector Machine, Random Forest Classifier provides a similar classification performance. This model classifies better for Group 1 consuming a small amount of electricity (less than 227 kWh per month) but worse for Group 2 consuming a large amount of electricity (more than 316.58 kWh per month).

The feature importance indicates that housing size is the most important feature for the household's electricity consumption, and the electricity consumptions of appliances, such as television, refrigerator, and air conditioner, are the next important features. Moreover, the expected monthly average electricity consumption of appliances is identified as high ranks in the feature importance as those directly affect the annual electricity consumption. From the feature importance, weather conditions, income group, and the number of members are the next important features.

Similarly, the decision tree classifier is applied to the annual electricity consumption of households grouped into three by k-means clustering. The optimal parameter of the

Decision Tree classifier for annual electricity consumption with three groups is ‘max_depth’ of 3 and ‘min_samples_leaf’ of 2. The accuracy of this classification is 0.576, which is very similar to Support Vector Classifier and Random Forest Classifier. Similar to the previous results, housing size is identified as the most important feature for classification, followed by income group and weather conditions. The first decision node is the housing size, and the next nodes are housing size and weather condition, which is heating degree days, for classification. Interestingly, this classification identifies the dummy variable for the aging factor, which indicates any presence of household members aged 65 or older, as one of the important features.

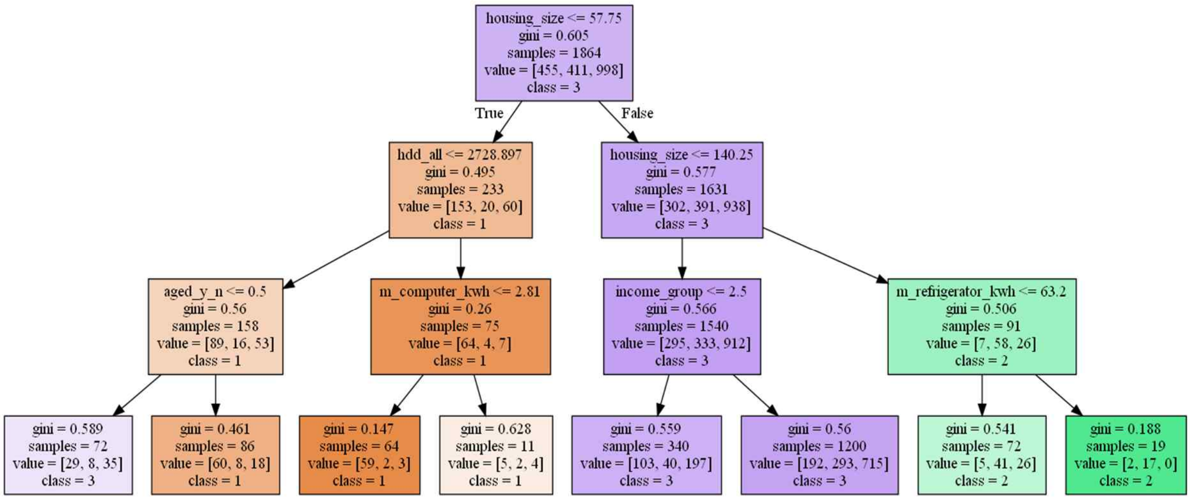


Figure 4 Decision Tree Classification
(Annual electricity consumption, group of three)

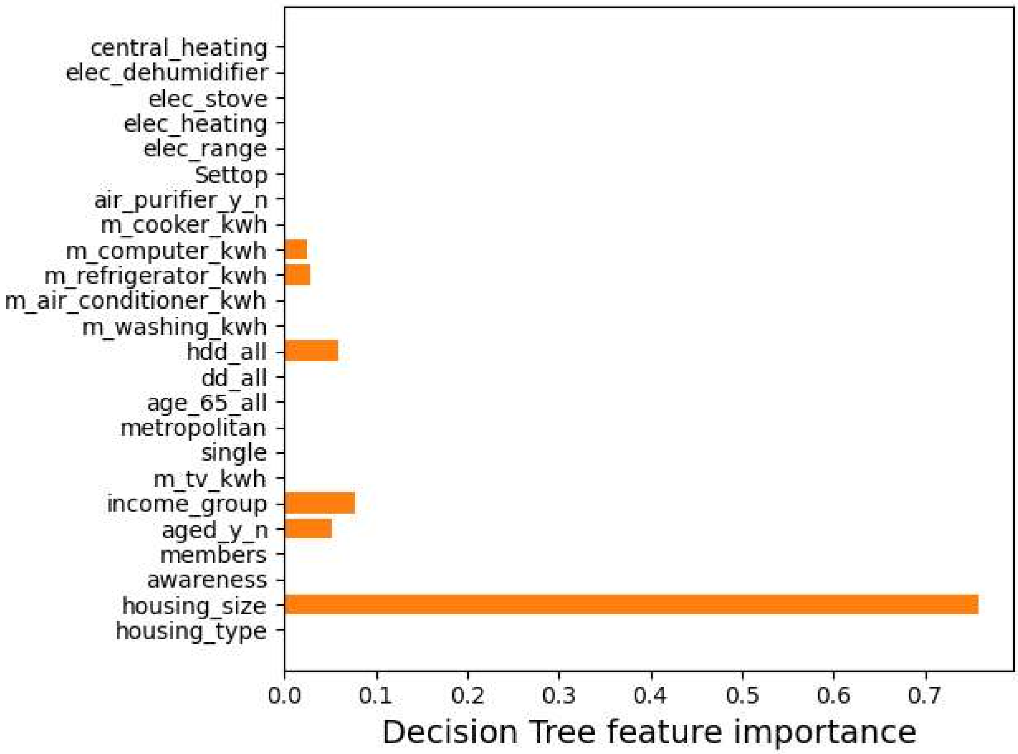


Figure 2-10 Decision Tree Classifier - Feature Importance

However, the classification results and performances of the Random Forest model and Decision tree are not remarkable, in general, as the accuracy and weighted average of the F1 score of those models stayed below 0.60 (60%). Typically, the models predicted and classified the observations in the test set as the typical group that contains the largest number of observations in the train set. This implies that even though the electricity consumptions of households are different, many of those households in the dataset have very similar characteristics, and the selected variables reveal only limited information of the behavior of household members. Therefore, this result would suggest improving the questionnaire of the survey by including more questions on the behaviors of household members.

The feature importance from Random Forest and Decision Tree indicates that housing size is the most important feature for the household's electricity consumption. Generally, the electricity consumption of appliances, such as televisions, refrigerators, and air conditioners, are the next important features. This result is similar to the findings from other literature (Kim 2020) and seems reasonable that a larger amount of energy is necessary for heating or cooling a larger housing area, and even with the similar compositions of appliances in households, the size of appliances might be different depending on the size of the housing. The manufacturers of appliances provide information on the appropriate size of housing for their appliances, and this would be a criterion for consumers when purchasing their appliances. Moreover, the expected monthly average electricity consumption of appliances is ranked high in the feature importance as those directly affect the annual electricity consumption. From the feature importance, weather conditions, income group, and the number of members are the next important features. Weather conditions, such as discomfort days and heating degree days, are also considered as an important variable as the use of air conditioners and electric heating appliances would be dependent on those weather conditions.

The level of income and number of members are identified as important characteristics affecting household electricity consumption not only in Korea but also in many other countries from other studies (McLoughlin, Duffy, and Conlon 2012; Huang 2015; Kim and Park 2015; Kim 2020). Though these do not tell how the residential electricity consumption is affected by those variables positively or negatively, feature importance shows those variables are important features for classifying the groups.

The study demonstrated the importance of demographic and household characteristics in electricity demand analysis. This suggests that the trends of aging and smaller households should be considered in demand forecasting and establishing energy policies. Without considering the estimated positive effects of those factors on residential electricity consumption, the demand forecasting would underestimate the future electricity consumption, and the energy plans and policies, which are established based on the underestimated electricity demand, would not provide the desired outcomes and results.

Moreover, housing characteristics, including type, would affect the residential electricity consumption significantly. Although the study considered housing characteristics in a limited scope, the result identified the importance of housing characteristics, such as the size of housing and apartment, in the residential electricity consumption. There can be a possible hidden relationship between the aging and smaller households and the housing type if there is a specific preference of aged individuals or small households on housing. In addition to the changes in household and demographic structures, Korean society expects a rapid change in various areas, including the further penetration of electric vehicles. It would significantly affect the understanding of electricity demand and increase the uncertainty in electricity demand forecasting. In further studies, as stated above, the factors affecting the electricity demand, such as housing characteristics and lifestyle, could be examined, and the analysis could consider the uncertainties of the future electricity demands caused by those factors.

3. AN ANALYSIS ON THE RESIDENTIAL ENERGY DEMAND IN KOREA

3.1 Introduction

Several previous studies have estimated the number of households based on the total population and used it for analyzing energy consumption with typical energy demand equations. However, the demographic structure and household structure have been changing rapidly in Korea. Especially, the trends of the aging population and the increase in single-person households have been accelerated in Korea (Noh and Lee, 2013; Statistics Korea, 2020). The key issues are not only the current share of the single-person households but also the expected acceleration of the increasing trend of the single-person households in the future. The share of the single-person households in Korea is expected to reach 35.7% by 2037, and the number of single-person households is expected to increase by about 100,000 annually by 2045 (Statistics Korea, 2020). 35% of the single households are in age groups of the 30s or below, and 31.5% of them are in age groups of 50s or above. The annual growth rate of income of the single-person household is higher than that of the entire household. However, the annual income of 78.1% of the single households is 30 million KRW or below. This simple finding indicates that single households aged the 30s or below tend to have a relatively higher income than those aged 50s or over (Statistics Korea, 2020).

In Korea, the household income has a strong relationship with the dwelling area. In 2019, the share of households living in the dwelling area of 60 m^2 or below in both the entire household and single-person household decreased compared to that of the previous year, while those living in dwelling area of 85 m^2 or above increased compared to the previous year. As residential energy consumption has a positive relationship with dwelling areas, residential energy consumption is likely to increase in the future (Won, 2012, Lee et al., 2015; Statistics Korea, 2020). Thus, the energy demand per household tends to increase as the dwelling area, the number of household members, and the household income increase (2017 Energy Census, p.141). The regression method is applied in the study to find the abovementioned relationships.

3.2 Methodology

The study used 8,253 residential data from the 2017 Energy Consumption Survey (Korea Energy Economics Institute and Korea Energy Agency, 2017) in Korea.
The residential sector of the Energy Census surveys general households, and the main survey items are housing, general information of households, energy consumption by source, the status of energy-consuming appliances, and so on. The main survey findings are energy consumption structure by region, housing type, the number of household members, and heating appliances, and energy consumption by usage (heating/cooking), etc. Moreover, the energy sources surveyed by Energy Census are coal, town gas, electricity, heat energy (local cooling and heating), renewable energy, and so on. The primary energy sources consumed by the residential sector are mostly electricity and town gas. While the use of city gas may vary depending on the type of housing surveyed, electricity can be used by all households. Therefore, this study conducted an analysis based on the annual consumption of electricity.

The projection of future energy demand by the residential sector is targeted for the year 2050. Since the Statistics Bureau, Korea provides the projection of households up to the year 2047. Thus, the study set year 2050 as the target year based on the assumption that the projections for the year 2047 are the same by 2050 (Statistics Korea, 2019a, 2019b).

The number of data used in the study is 8,253 observations. Among them, the study checked the outliers in the dependent variable and excluded observations with outliers from the dataset. The total number of observations excluding those with outliers is 8,072. The following formula is used for calculating the response variable (dependent variable) to analyze the electricity consumption per capita.

$$Energy\ Consumption\ per\ capita = \frac{Annual\ Electricity\ Consumption\ per\ Household\ (Calorie\ base)}{Number\ of\ household\ members}$$

The study considered variables, such as gender of household head, age of household head, the highest level of education of household head, number of economically active household members, the composition of household members, characteristic of household members, the average amount of cooked at a time, average monthly income, as the candidates for explanatory variables (independent variables). The study found eight missing values in those candidates and replaced all missing values with zero. To conduct EDA (Exploratory Data Analysis), the study used a correlation coefficient matrix and box plot to find the relationships among variables. To reflect the temperature difference by region, the regression of energy demand is conducted using dummy variables by region.

Based on the regression analysis, the study projected the current and future residential energy consumption. Each composition of households' type is applied as a dummy variable. The study derived the energy consumption per capita for each composition of households' type. When deriving energy consumption, the value of the independent variable used the average value. The forecast uses the population and household projections provided by Statistics Korea. Except for the population and the composition of household type, which are projected values, the other variables used in the study are the current values.

The following formula is applied to calculate the residential energy consumption:

*Residential Energy Consumption =∑(energy consumption per capita by household type * number of household members by household type * household number by household type)*

The average number of household members by household composition is 2 persons for Type 1, 3.67 persons for Type 2, 4.99 persons for Type 3, 2.41 persons for Type 4, and 2.87 persons for Type 5.

3-3 Regression Results

The regression result of the heat energy consumption in the residential sector is shown in Table 3-1. Table 3-2 is for the regression result of electricity consumption. In general, the per capita heat energy consumption and the per

capita electricity consumption have positive correlations with the age of the head of the household. However, it is worth noting that a convex curve is drawn with respect to age for the energy consumption, since the sign of the age squared term is negative and statistical significant. In Table 3-1, it is also found that the average household income has a strong positive relationship with the heat energy consumption and a negative correlation with the number of economically active household members who are actively engaged in economic activities. It is statistically significant that the negative coefficients of regional dummy variables in southern parts of Korea indicate the temperature effect to estimate the heat energy demand in the residential sector.

Independent variable	Coefficient	t-statistic	p-value
Head of Household's age	48.7708	3.352	0.001
Head of Household's age square	-0.3565	-2.669	0.008
One generation household (Dummy)	1084.89	3.851	0.000
Two generation household (Dummy)	-98.5663	-0.349	0.727
Three generation household (Dummy)	-777.285	-2.551	0.011
Single parent family (Dummy)	541.0491	1.789	0.074
Other type of households (Dummy)	-269.546	-0.868	0.385
Monthly average gross income	120.8762	8.478	0.000
Number of household members (Economic Activity)	-197.794	-4.041	0.000
Non-single (Age 31-64) (Dummy)	-40.7332	-0.367	0.713
Non-single (Age below 30) (Dummy)	390.1729	1.36	0.174
Single (Age below 30) (Dummy)	2020.608	6.623	0.000
Single (Age 31-64) (Dummy)	2574.361	8.793	0.000
Single (Age over 65) (Dummy)	3414.698	12.4	0.000
Seoul (Dummy)	239.8681	1.761	0.078
Busan (Dummy)	-948.233	-6.112	0.000
Daegu (Dummy)	16.755	0.103	0.918
Incheon (Dummy)	-551.835	-3.433	0.001
Gwangju (Dummy)	1228.341	6.599	0.000
Daejeon (Dummy)	1338.091	7.256	0.000
Ulsan (Dummy)	-371.022	-1.914	0.056
Sejong (Dummy)	-43.9732	-0.173	0.863
Gyunggi (Dummy)	444.4845	3.33	0.001
Gangwon (Dummy)	1516.953	8.409	0.000
Chungbuk (Dummy)	1587.002	8.864	0.000
Chungnam (Dummy)	942.1173	5.719	0.000
Jeonbuk (Dummy)	1464.202	8.635	0.000
Jeonnam (Dummy)	2014.732	11.495	0.000
Gyungbuk (Dummy)	914.554	5.677	0.000
Gyungnam (Dummy)	-470.842	-3.014	0.003

Jeju (Dummy)	-830.987	-3.827	0.000

Table 3-1 Polynomial Nonlinear Regression Result on Heat Energy Consumption

Note 1: The dependent variable is Energy consumption per person in households, and Adjusted R2: 0.275(F-statistics: 105.4).
Note 2: The base of the Composition of households' type dummy is a single-person household

In Table 3-2, it is found that the working-aged single family consumes relatively more electricity demand at home with strong statistical significance. The income effect is positive as expected, and the regional dummy variables show a positive impact on power electricity consumption in the residential sector.

Independent variable	Coefficient	t-statistic	p-value
Head of Household's age	10.9222	4.938	0.000
Head of Household's age square	-0.0745	-3.668	0.000
One generation household (Dummy)	579.2255	13.543	0.000
Two generation household (Dummy)	94.2424	2.201	0.028
Three generation household (Dummy)	-70.1656	-1.514	0.130
Single parent family (Dummy)	372.7901	8.117	0.000
Other type of households (Dummy)	273.0854	5.798	0.000
Monthly average gross income	17.2624	7.933	0.000
Number of household members (Economic Activity)	-51.6631	-6.947	0.000
Non-single (Age 31-64) (Dummy)	19.671	1.167	0.243
Non-single (Age below 30) (Dummy)	120.4828	2.756	0.006
Single (Age below 30) (Dummy)	1121.983	24.489	0.000
Single (Age 31-64) (Dummy)	1325.477	29.777	0.000
Single (Age over 65) (Dummy)	1365.31	32.62	0.000
Seoul (Dummy)	262.9464	12.694	0.000
Busan (Dummy)	335.5815	14.219	0.000
Daegu (Dummy)	280.8581	11.415	0.000
Incheon (Dummy)	283.8727	11.561	0.000
Gwangju (Dummy)	391.7838	13.736	0.000
Daejeon (Dummy)	336.9808	12.072	0.000
Ulsan (Dummy)	258.5942	8.753	0.000
Sejong (Dummy)	295.5512	7.569	0.000
Gyunggi (Dummy)	266.3002	13.137	0.000
Gangwon (Dummy)	362.0907	13.308	0.000
Chungbuk (Dummy)	315.0959	11.701	0.000
Chungnam (Dummy)	226.9515	9.109	0.000
Jeonbuk (Dummy)	202.3319	7.819	0.000
Jeonnam (Dummy)	256.3632	9.638	0.000
Gyungbuk (Dummy)	343.1467	14.203	0.000
Gyungnam (Dummy)	317.6466	13.376	0.000
Jeju (Dummy)	325.8522	9.642	0.000

Table 3-2. Polynomial Nonlinear Regression Result on Electricity Consumption

Note 1. The dependent variable is Energy consumption per person in households, and Adjusted R2: 0.636(F-statistics: 484).

Note 2. The base of the Composition of households' type dummy is a single-person household

In 2017, the per capita total energy consumption in Korea was about 4,505 Mcal, on average, in the residential sector, as shown in Figure 3-1. It is worth noting that the average energy consumption of a single-family household is the highest at about 7,365 Mcal, followed by one generation family (5,251 Mcal), three-generation households (4,501 Mcal), other type of households (3,591 Mcal), and two-generation households (3,583 Mcal), and single-parent family (2,740 Mcal) in that order. This is obvious that as the family members share energy consumption, the average energy consumption of the households with more family members becomes lower. Also, as the head of a household is older, the total energy consumption per capita becomes higher. In particular, the shares of the heat energy and electricity use of the group with age less than 30 and the group with age between 31 and 64 group are approximately 71.9%, 72.0%, 28.1%, and 27.9%, respectively, which are almost the same. However, the share of heat energy for the group with age over 65 is relatively higher, reaching 74.6%. (See Figure 3-1.)

Total energy consumption in the residential sector in 2017 was about 19.4 billion Gcal, of which 7.5 billion Gcal (38.6%) for two-generation households, 4.1 billion Gcal (21.1%) for single-person households, and 3.1 billion Gcal for one-generation households (16.0%), 2.1 billion Gcal (10.6%) for single-parent families, 1.5 billion Gcal (7.8%) for other type households, and 1.1 billion Gcal (5.9%) for three-generation households (See Figure 3-2.). Based on the regression result and the projection of independent variables, the total energy consumption in year 2047 in the residential sector is expected to be about 21.1 billion Gcal, an increase of about 8.9% compared to that of 2017. In particular, single-person households are expected to increase by 57.2%, and one-generation households are expected to increase by 56.7%. The rapid increase of single-person households in 2047 takes accounts for 53.5% of the total energy consumption in the residential sector.

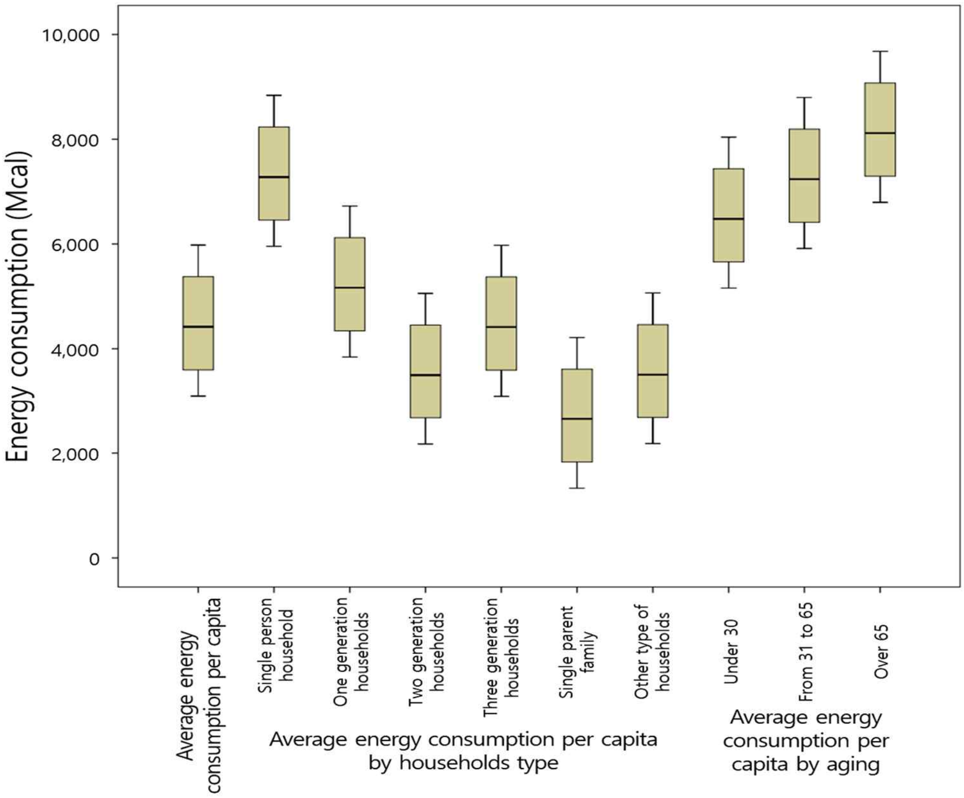


Figure 3-1 Comparison of per capita Energy Consumption (2017)

The energy consumption patterns are different from the characteristics of the head of the household. The total energy consumption of single-person households would increase by 57.2% from about 4.1 billion Gcal to about 6.4 billion Gcal between 2017 and 2047. The heat energy consumption of the group with age between 31 and 65 is about 1.7 billion Gcal (40.9). However, it is worthwhile to note that the heat energy consumption of the group with age over 65 is to increase about three times from about 800 million Gcal in 2017 to 2.5 billion Gcal (See Figure 3-2.).

Changes in energy consumption between 2017 and 2047 according to the age of single-person households are expected to increase for people aged 65 and over. It implies that this finding is implicitly related to the increase of single-person households and the increasing trend of the aging society in Korea.

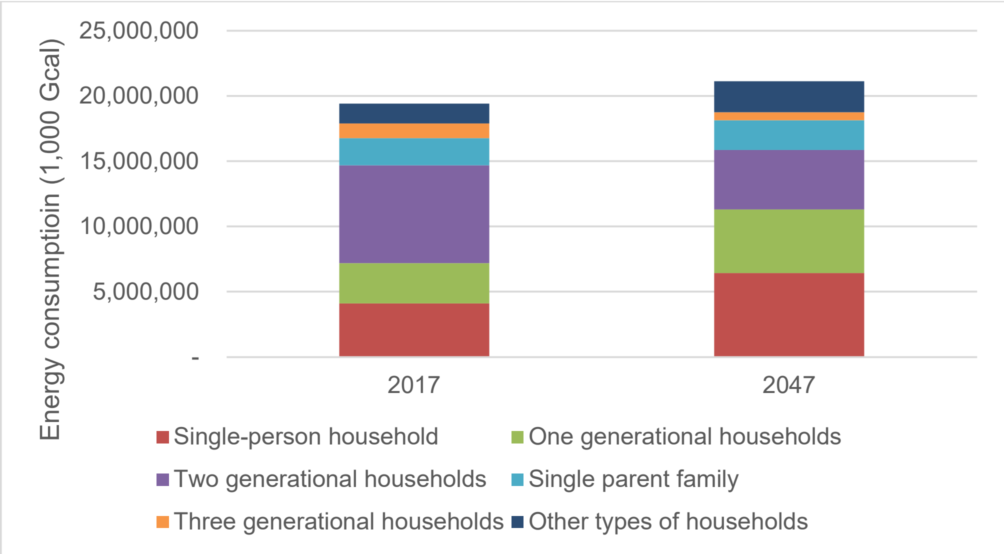


Figure 3-2 Total Energy Consumption by Household Type

Figure 3-3 shows the heat energy consumption and electricity consumption in the residential sector between 2017 and 2047 by the number of family members in households and by age. The energy use of the single-person households is the highest, followed by 1st generation, 3rd generation, 2nd generation, others, and single-parent families. By age, the energy consumption of a household aged 65 and over has the largest share. It is found that the increase of single-person households and the aging population are closely related to the future energy consumption in the residential sector. Since the electrification and power energy demand is to increase due to the digital transformation, the power energy consumption is to increase (See Figure 3-3.).

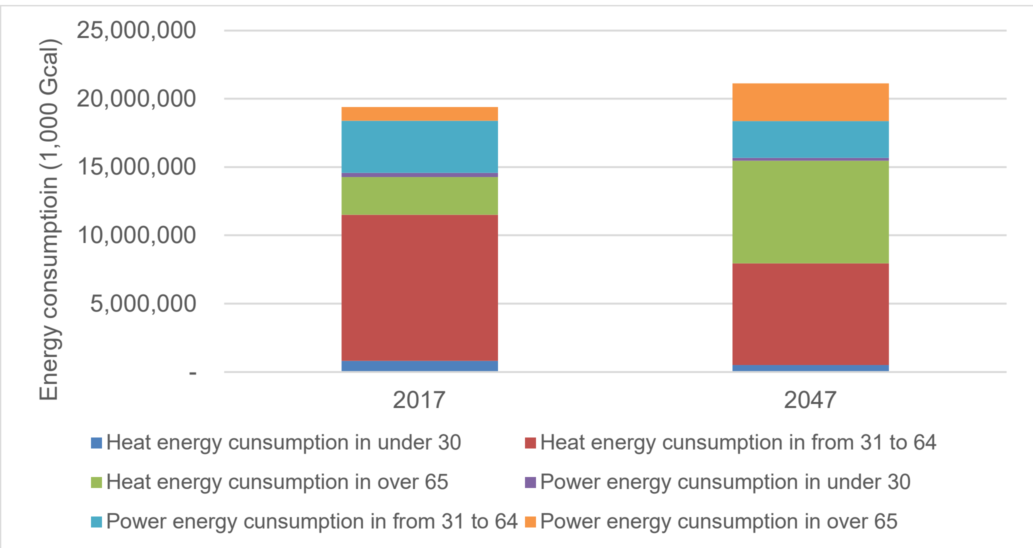


Figure 3-3 Heat and Power Energy Consumption by Household Type

The energy consumption in the residential sector is to increase due to the aging effect. It is found that the peak of heat energy consumption is at age 68.4, and that of electricity consumption is at age 73.3 (See Figure 3-4.). Although there are many studies (Won, 2012; Yamasaki and Tominaga, 1997) on the change in electricity and energy consumption led by an aging factor, this study also finds household types, number of household members as the independent variables in the regressions. This study also finds a similar effect of age to those previous studies.

It found a negative correlation between the number of family members doing economic activities and the energy consumption because intuitively, more family members are spending time outside. On the other hand, the number of family members doing economic activities may increase the family income, but there is no statistically significant relationship between family income and energy consumption in a household.

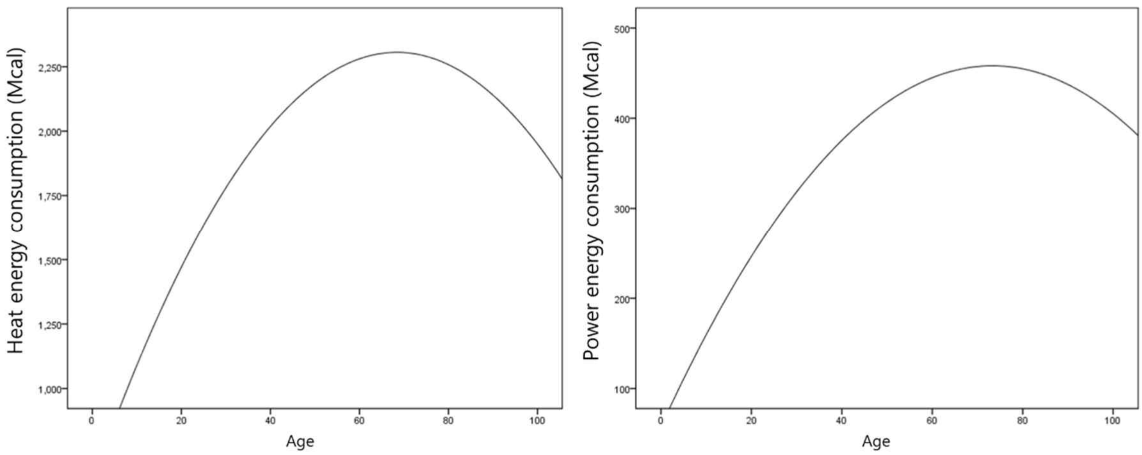


Figure 3-4 Energy consumption curve by age

In this study, energy consumption is estimated by reflecting various socio-economic changes, such as changes in the number of people and household characteristics in the residential sector. To estimate the future energy consumption in the residential sector, more socio-economic factors, such as the distribution of the aging group, the share of single-person families, and the projection of the population itself should be further elaborated. This study reaffirmed that the per capita energy consumption of single-person households is higher than that of other types of households. There is some basic energy demand for any household. It is also found that the consumption of both heat energy and power energy decreases after the peak of a certain age.

4. IMPACT OF LOW ENERGY DEMAND ON SDGS IN KOREA

Demographic changes, including the size of the population, age structure, and household characteristics, have become an important issue in many countries. The demographic transitions of Korea have accelerated recently due to the low fertility rates and longer life expectancies. As human behavior affects energy consumption and carbon emissions via various channels, an understanding of the impacts of demographic changes on energy demand and carbon emissions is necessary to forecast the future CO2 emission profiles of Korea.

4.1 Low Energy Demand Trend

The total primary energy supply in Korea has steadily increased since the economic activities in Korea keep growing. However, it is worth noting that the total primary energy supply started decreasing in 2019 and 2020 consecutively, mainly due to the shrink of economic activities caused by COVID-19. In addition, a strong decarbonized policy accelerates the decrease of coal demand in the power generation sector. The share of coal shows a decreasing trend. To make up the coal-fired power plants, the portions of natural gas and renewables are increasing, which is a strong signal that Korea is keen on decarbonization, as well as low energy demand. The decreasing trend of oil demand is also remarkable in Korea. Recently, the share of oil has become less than 20% of the total primary energy supply. The promotion of renewable energy sources such as solar and wind is one of the key energy policies in Korea (See Figure 4-1.).

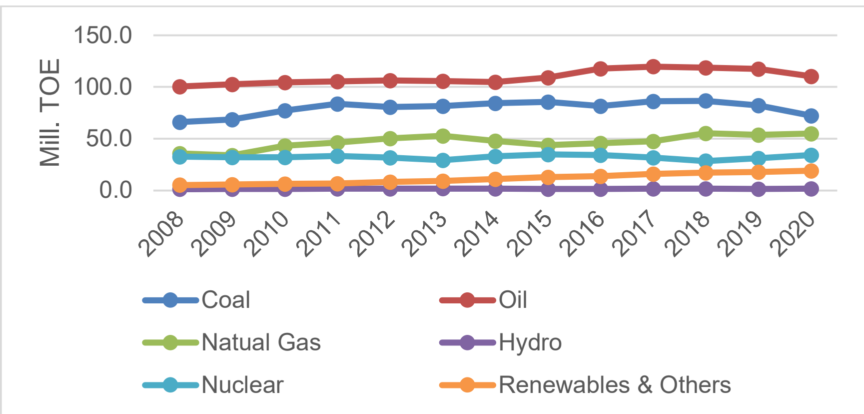


Figure 4-1 Total Primary Energy Supply

The final energy demand in Korea has steadily increased since the economic activities in Korea keep growing. However, like the total primary energy supply, it is decreasing in 2019 and 2020 consecutively, mainly due to the shrink of economic activities caused by COVID-19. Still, more than 60% of the final energy is demanded in the industrial sector, which makes it very difficult in Korea without changing the industrial structure. Most energy uses in the industrial sector are allocated to energy-intensive industries such as iron-steel, cement, and petrochemical ones. In addition, the strong promotion of low-carbon vehicles, including electric vehicles, contributes to the lower energy demand in the transportation sector. The energy demand in commercial buildings and residential ones is relatively stable (See Figure 4-2.).

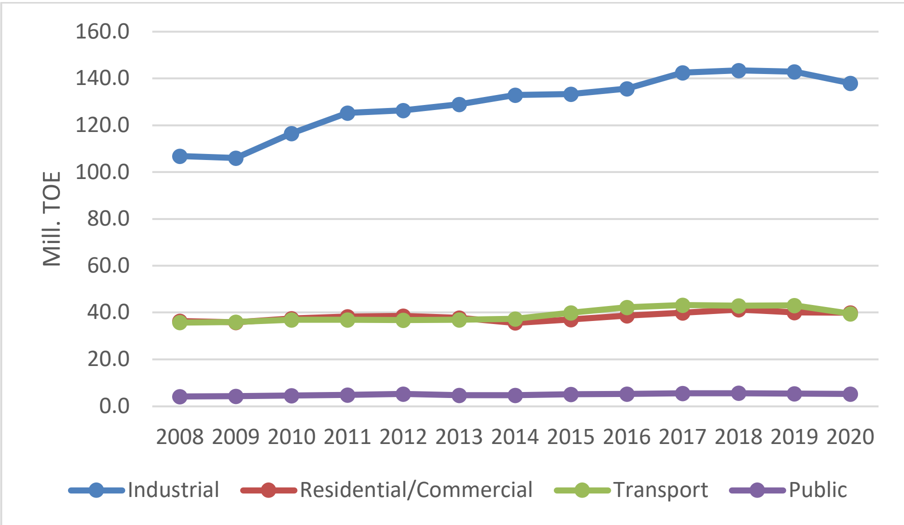


Figure 4-2 Total Final Energy Demand

4.2. Low Energy Demand Projection

4.2.1 Nationally Determined Contribution (NDC)

In accordance with the Paris Agreement, on December 30, 2020, the Republic of Korea (ROK) communicated its updated NDC that had replaced its BAU-based reduction target with an economy-wide absolute emissions reduction target to contribute to the faithful implementation and achievement of the goals of the Paris Agreement.

The enhanced update of the first NDC of ROK is set at the most ambitious level possible to achieve the goal of carbon neutrality by 2050 despite the country's manufacturing-based industrial structure. The updated and enhanced emission reduction target is to reduce total national GHG emissions by 40% from the 2018 level, which is 727.6 $MtCO_2eq$, by 2030. This 40% emission reduction target is more enhanced because it is below its linear reduction pathways from 2018 to 2050. This indicates the Republic of Korea's enhanced ambition towards the goal of carbon neutrality by 2050. In September 2021, ROK enacted the Framework Act on Carbon Neutrality and Green Growth for Climate Crisis Response (or "the Carbon Neutrality Act"), enshrining the minimum level of a mid-term national GHG emission reduction target as well as a robust implementation mechanism in law to ensure faithful implementation of its NDC. Below are the key updates of the Republic of Korea's NDC. (See Figure 4-3.)

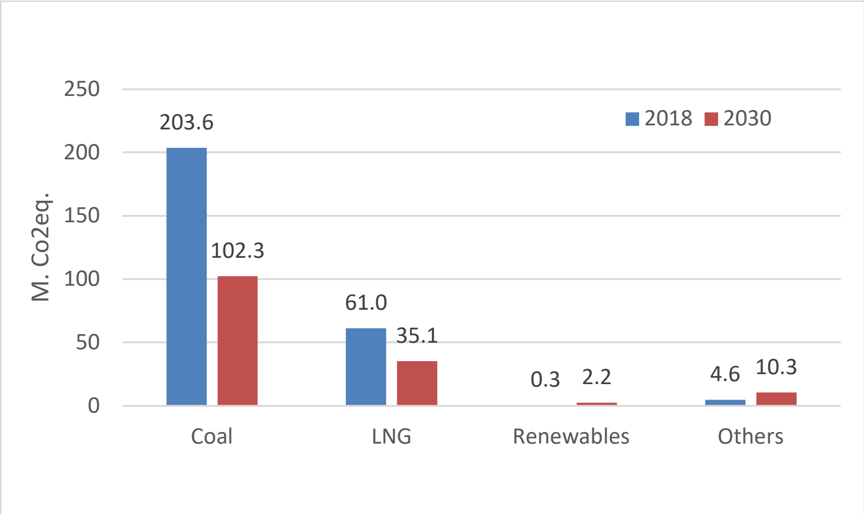


Figure 4-3 GHG Emission Target for 2030

The Republic of Korea is significantly enhancing its 2030 target from the previous 24.4% reduction compared to the 2017 level (26.3% reduction from the 2018 level) up to 40% reduction from the 2018 level. In setting the updated NDC, the entire sectors' CO_2 mitigation potentials have been analyzed and fully reflected possible. The following are key mitigation strategies for achieving the new 2030 target by sector (See Table 4-1.).

1) Power generation: The Republic of Korea is seeking to dramatically phase down coal-fired power generation while ramping up renewable power. Aged coal power

plants will be shut down or shift their fuels from coal to Liquefied Natural Gas (LNG). The uptake of solar and wind power will be scaled up as well. The Korean government will also support research and development of improving the efficiency of major renewable energy facilities and make a preemptive investment in improving power grids. The target emission limit for the power sector is set at 149.9 million tons CO_2eq, which is lower than the 2018 level by 44.4%.

2) Industry: The Republic of Korea is focusing on driving a low-carbon transition in emission-intensive sectors, i.e., steelmaking, petrochemicals, and cement industries. In industrial production processes, electric furnaces are expected to be used to reduce emissions, and bio-naphtha will be increasingly used as a feedstock for petrochemical crackers instead of naphtha. In the cement industry, the energy-saving rate is set to be improved, and waste synthetic resin will be used for reduced consumption of fossil fuels. Facilities to reduce fluorinated GHG emissions from the semiconductor and display industries will be expanded.

3) Building: The Republic of Korea is stepping up efforts to promote zero-energy building solutions for newly constructed buildings and encourage the widespread implementation of green remodeling projects on existing buildings. In line with these efforts, the Korean government will strive to improve energy efficiency, including through the distribution of energy-efficient lighting systems and appliances, and actively introduce new and three renewable energy sources, including solar photovoltaic, geothermal, and hydrothermal energy.

4) Transportation: The Republic of Korea has markedly raised its 2030 target on the deployment of zero-emission vehicles such as the ones powered by electricity and hydrogen. In tandem with this, the Korean government is seeking to reduce trips by car, including through the improvement of public transportation services. In the shipping and aviation sectors, emission reduction efforts will be focused on distributing eco-friendly ships and enhancing the operational efficiency of aircraft.

5) Agriculture, livestock farming, and fisheries: The Republic of Korea is introducing various options to accelerate low-carbon farming, for instance, improving irrigation techniques in rice paddies and adopting low-input systems for nitrogen fertilizers. As viable mitigation options, enhancing treatment methods for livestock excreta or turning them into energy sources as well as introducing forage that contributes to lower methane emissions are being explored in livestock farming. The Korean government is aiming to adopt highly efficient facilities to consume less energy in

this sector.

6) Waste: The Republic of Korea's waste management policy focuses on reducing waste generation while increasing recycling. The existing petroleum-based plastics will be replaced by bioplastics, and methane gases emitted from landfills will be recovered for use as an energy source.

7) Carbon sinks (LULUCF): The Republic of Korea will maintain and improve its carbon sinks with sustainable forest management, conservation, and restoration and increase forestlands by greening urban spaces. Other options include creating new coastal and inland wetlands as well as vegetation in waterfront areas.

(Unit: Million ton CO2eq)

Sector		2018	Previous NDC (Change from 2018)	Updated NDC (Change from 2018)
Emission amount		727.6	536.1 (△191.5, △26.3%)	436.6 (△291.0, △40.0%)
Sources	Power	269.6	192.7 (△28.5%)	149.9 (△44.4%)
	Industry	260.5	243.8 (△6.4%)	222.6 (△14.5%)
	Building	52.1	41.9 (△19.5%)	35.0 (△32.8%)
	Transportation	98.1	70.6 (△28.1%)	61.0 (△37.8%)
	Agriculture	24.7	19.4 (△21.6%)	18.0 (△27.1%)
	Waste	17.1	11.0	9.1

			(△35.6%)	(△46.8%)
	Hydrogen	-	-	7.6
	Fugitive	5.6	5.2	3.9
Sinks and others	Sink	41.3	-22.1	-26.7
	CCUS	-	-10.3	-10.3
	Foreign Credit	-	-16.2	-33.5

Table 4-1 The Target Emission Limits by Sectors under the Updated NDC

4.2.2 Change of Energy Demand Projection by Demographic Factor[2]

Demographic changes have become an important issue in Korea, where the decreasing trend of the population has accelerated recently due to the low fertility rates. The key research question of this study is to examine how the changes in demographic characteristics affect the future energy intensity in Korea by comparing one component of the Kaya Identity, which is measured by the energy intensity with the six population projection scenarios by UN. This study adopts population projections from the UN Population Prospects 2010 and 2019 to the constructed CGE model. This study focuses on the impact of the demographic changes on the energy intensity that can be extracted from the CGE modeling. This study constructs a dynamic CGE model and applies the most up-to-date dataset, such as the UN Population Prospects 2019, GTAP 10, and labor force participation rates from ILO to examine the research question. Then, the Kaya Identity is applied to compare the energy intensity due to the change of demographic characteristics on the economy, energy consumption measured by the final energy demand, and carbon emission of Korea.

Six scenarios were constructed to evaluate the emission impacts of the change in demographic trends in the years up to 2100. We considered two UN projections, one

---

[2] This part is based on the modeling results of the published paper, “The Impact of Demographic Changes on CO_2 Emission Profiles: Cases of East Asian Countries”, Tae Yong Jung, Yong-Gun Kim and Jongwoo Moon, *Sustainability*, 2021, 13, 677

from 2010 and the other from 2019, and three scenarios for each of the two projections: high, medium, and low growth scenarios. The year 2010 was chosen to base our study on the shared socio-economic pathways (SSP) scenarios, which is based on UN 2010 population projections. The year 2019 is the latest year with UN population projection data. We can evaluate the GHG emission impacts from the change of demographic forecasts in the recent nine years and understand the policy implications of the recent trend of the population in terms of climate mitigation and adaptation.

The baseline scenario (named 2010MID) was constructed based on the UN 2010 medium projection of population. Total factor productivities of individual regions were calibrated to reproduce the real GDP forecast by OECD for the SSP2 scenario. Labor force participation rates by age groups by the International Labor Organization (ILO) were applied to quantify the magnitude of labor supply in the CGE model. The labor supplies from individual age groups were assumed to be the product of population size and labor participation rates. The alternative scenario was constructed with the recent 2019 UN projection of population (named 2019MID). We can investigate the impact of the change of the demographic projection on labor supply and GHG emissions thereafter. High and low growth projection scenarios were also considered for evaluating the implications of population variability, and four more scenarios were established: 2010LOW, 2010HIGH, 2019LOW, and 2019HIGH. Since the population projections in Korea by the end of this century vary from 20 million people to over 60 million people, the population projection itself obviously affects the projections of energy demand and CO_2 emissions. The CGE model constructed in this study captures the change of key variables such as final energy demand and CO_2 emissions with different population projection scenarios (See Figure 4-4.).

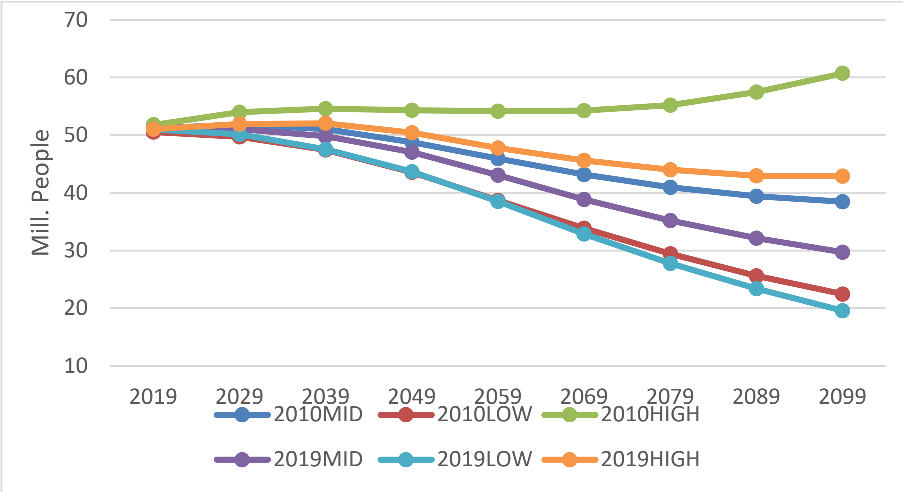


Figure 4-4 Population Projection by Scenarios

Different population projections will affect the production side of an economy by changing the number of the labor force, which is an input factor of the production functions. In CGE modeling, input factors and productions functions determine the level of GDP and final energy demand. With different population scenarios, the different final energy demand projections are shown in Figure 4-5. The gap of final energy demand gap between 2010HIGH and 2019LOW scenarios seems to be about 30% at the end of this century.

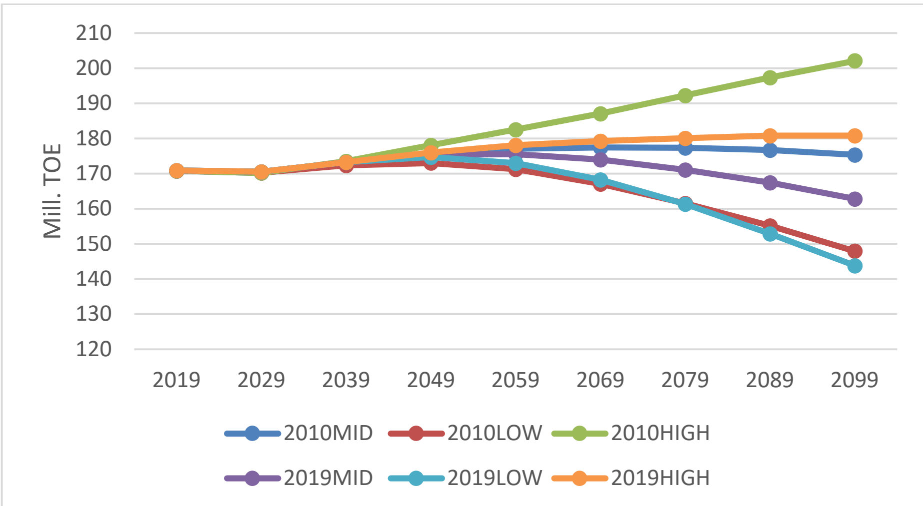


Figure 4-5 Final Energy Demand Projection by Scenarios

To obtain the projections for energy demand and GDP, a dynamic computable general equilibrium (CGE) model was constructed to examine the effects of aging populations on energy consumption and carbon emissions. In general, a CGE model consists of a system of equations, describes the interactions among parts of an economy systematically, and solves the equations to find the economy-wide equilibrium. A strong feature of CGE model-based analysis is that it enables the induction of quantitative effects of shocks, such as policy changes, with real data, so the CGE model is widely used in various areas of energy and GHG emissions research. The decomposition analysis, which is well known as the Kaya Identity, is conducted based on the components calculated from the CGE model results.

The Kaya identity is an identity to decompose the total GHG emissions (or CO_2) level into four factors, such as, carbon intensity, energy intensity, GDP per capita, and population. It is commonly expressed as a simple identity form.

$$CO2 \equiv (CO2/ENERGY)*(ENERGY/GDP)*(GDP/POPULATION)*POPULATION$$

$$CO2 \equiv (CI)*(EI)*G*P$$

where *CI* is the carbon intensity, *EI* is the energy intensity measured by the final energy demand, *G* is the per capita GDP, and *P* is the population.

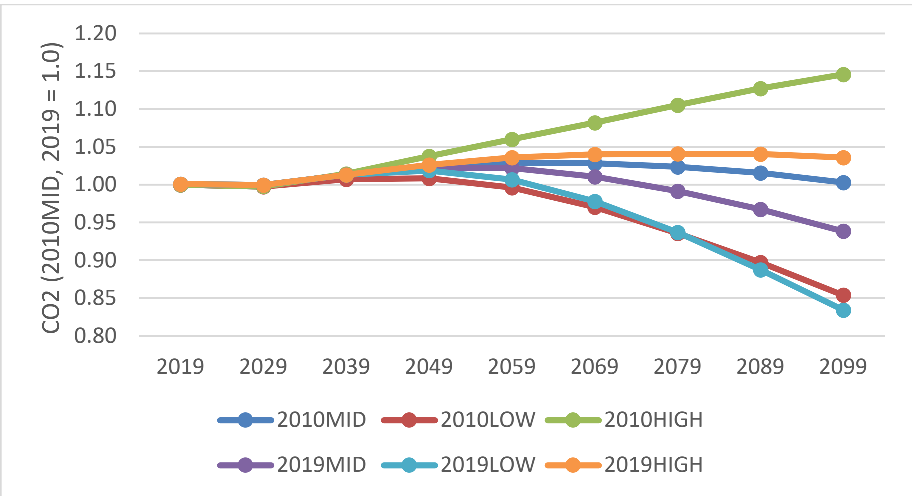


Figure 4-6 Change of CO_2 emissions by Scenarios

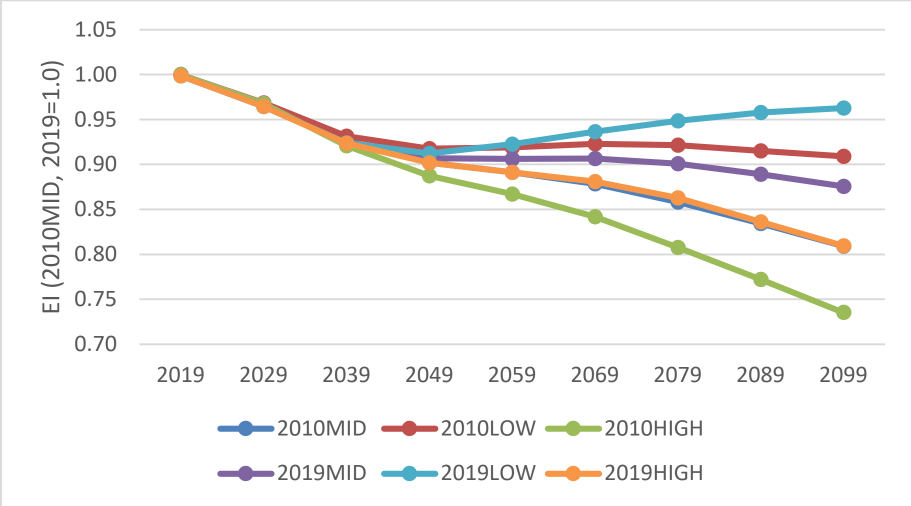


Figure 4-7 Change of Energy Intensity by Scenarios

4.3. Sustainable Development Goal (SDG) Analysis

4.3.1 Methodology[3]

The vast literature on SDGs describes it as a multi-dimensional concept that is captured by numerous predefined sub-targets and indicators. Yet, a quantitative methodology designed to evaluate the performance of SDGs across countries based on a common scale is not available in the analysis of the SDGs. In this report, we apply a statistical method, called Factor Analysis (Principal Component), to develop indexes to measure ROK's past and future trajectory in achieving the SDGs that are related to the energy demand.

Factor analysis will be used as the main tool to create a SDG index. Factor analysis is a statistical method to explain variability among observed and correlated variables in terms of a potentially lower number of unobserved variables called factors. Yearly time-series data were collected according to the official list of SDG indicators composed by the UN Inter-Agency and Expert group. Each SDG has 3 to 19 sub-goals that specify each goal; each sub-goal also has up to three indicators that can be used

[3] The methodology of this section is based on ther chapter 2, *Sustainable Development Goals in the Republic of Korea*, edited by Tae Yong Jung., Routledge, 2018. The analysis is done with the updated data.

to evaluate the sub-goal. For this report, we select SDG 7, which is directly related to the energy demand. We made a distinctive decision for unavailable indicators. They are either replaced by one or more other proxy variables that could logically approximate the indicators or are dropped from the analysis. There are three reasons some indicators were not available.

Some of the data collected included missing points. Either the data started from a later time or had missing values in between. For variables that were kept but still have some missing values, imputation methodologies were conducted to fill in missing points. Since there is no satisfactory method to impute panel data that preserves both the variance of the data and time-related properties, this study used a combination of two imputation methods. Once the two imputation methods were conducted, the mean value of the two results replaced the missing values of the indicators. The two methods used for the imputation process are as follows.

1) Linear interpolation imputation is firstly used for estimating the missing values. It is briefly defined as the estimation of missing values of one variable based on its linear relationship with another variable. For example, to estimate missing value x_0 between known values x_1 and x_2 in a vector X and the known vector Y, with y_0, y_1, and y_2 corresponding to x_0, x_1, and x_2, respectively. Then we can estimate x_0 by the following calculation.

$$\frac{x_0 - x_1}{y_0 - y_1} = \frac{x_2 - x_1}{y_2 - y_1}$$

Since x_0 is the only unknown value in the equation, we can easily estimate the value for x_0 by assuming that both X and Y vectors are linear polynomials.

2) The second imputation method used was a regression-based imputation. A simple regression model is used with the variable of the estimated missing values as the dependent variable. The composition of independent variables varied according to the dependent variable to best estimate the fitted value of the regression.

After the imputation process, we standardized each variable so that it had mean ($\bar{x}$) and standard deviation (σ), 0 and 1, respectively. Each data point was calculated based on the standardization method calculation as shown below.

$$x' = \frac{x_a - \bar{x}}{\sigma}$$

Since the transformation of a real value into normalized data points could create negative values, the final index values for each SDG can be negative in certain years. If more than one indicator was prescribed to the sub-goals in each SDG, variables were aggregated according to the authors. Additionally, to set all variables into a common range, data rescaling methods were applied to certain variables. Most of the data were in percentage form. These variables were kept as is while the other variables, which were on different scales, were also brought in line with the 0–100 range.

Factor analysis explores the joint variations within the observed variables in response to unobserved latent variables. The observed variables are assumed as linear combinations of the potential factors and error terms. Factor analysis aims to find independent latent variables. The objective of applying the factor analysis is that the information gained about the interdependencies between observed variables can be used later to reduce the set of variables in a dataset. At the initial stage, there are too many variables to conduct research, and in fact, there is no prior information on the relationship among observed variables. Then, the relationship among unobserved latent variables can be identified by a minimum number of factors. Factor analysis is not used to any significant degree in physics, biology, and chemistry, but it is used very heavily in psychometrics personality theories, marketing, product management, operations research, and finance, where unobserved variables may play an important role in understanding the social phenomena or human behavior being studied.

Factor analysis works with data sets where there are large numbers of observed variables thought to reflect a smaller number of underlying/latent variables. It is one of the most used interdependency techniques; it is used when the relevant set of variables shows a systematic inter-dependence, and the objective is to find the latent factors that create a commonality. In some disciplines, factor analysis and another statistical method, principal component analysis (PCA), are used interchangeably. The principal component analysis is typically used if the goal of the analysis is to simply reduce correlated observed variables to a smaller set of important independent composite variables. The PCA's eigenvalues are essentially inflated component loadings of factor analysis.

Technically, with imputed, standardized, and representative indicator variables for each sub-goal, we ran a factor analysis for each SDG. The main purpose of conducting a factor analysis was to determine the proper weights for sub-goals under each SDG so an index for each SDG could be created based on the actual data of the ROK. The brief process of factor analysis was as follows. (Harman, 1976)

$$\frac{X-\mu}{\sigma^2} = Z = LF + \epsilon \quad (1)$$

X is a matrix of sub-goal indicator variables under one SDG.

μ is a matrix of mean variables of the sub-goal indicators.

σ^2 is a matrix of variance of the sub-goal indicators.

F is a matrix of factors, unobserved random variables.

L is a matrix of factor loadings, unobserved constants.

ϵ is a matrix of error terms.

The analysis holds the following assumptions.

- F and ϵ are independent.
- $E(F) = 0$
- $Cov\,(F) = I$ (identity matrix, assuming factors are not correlated).

We square each side of equation (1), then since Cov(F) = E[(F−E(F)(F−E(F)^T] = E(FF^T) = I, we have equations (2) and (3).

$$ZZ^T = L(FF^T)L^T + \epsilon\epsilon^T = LL^T + \epsilon\epsilon^T \quad (2)$$

$$[\epsilon\epsilon^T]^2 = (ZZ^T - LL^T)^2 \quad (3)$$

We find LL^T, a set of factor loadings that minimizes the square error terms.

The results of the factor analysis loading of each factor for each indicator variable were used to calculate the weighting of the index for this study. Factor loading indicates how well the unobserved factor explains the corresponding indicator variable. Therefore, the higher the factor loading, the better the factor explains corresponding indicator variables. The highest factor loadings for each indicator variable were selected and squared. The value of squared factor loading is the weight for the indicator. Finally, the weighted sum of all indicator variables becomes an index for the SDG.

4.3.1 SDG 7

Energy is one of the essential key drivers for economic and social activities. Basic services for human activities are not affordable without a reliable and sustainable energy supply. However, unfortunately, fossil fuel energy is the main global energy source, which is the key contributor to global warming. The United Nations General Assembly recognized energy services as one of the important drivers to achieve sustainable development goals (SDGs). The SDG 7 was adopted to “ensure access to affordable, reliable, sustainable, and modern energy for all by 2030.” (UN General Assembly, 2015) SDG 7 is composed of five outcome targets (7.1 – 7.3, 7.A, and 7.B) with six indicators.

Access to Electricity

- Target 7.1 “By 2030, ensure universal access to affordable, reliable and modern energy services.”
- Indicator 7.1.1: Proportion of population with access to electricity
- Indicator 7.1.2: Proportion of population with primary reliance on clean fuels and technology

Renewable Energy

- Target 7.2. “By 2030, ensure universal access to affordable, reliable and modern energy services.”
- Indicator 7.2.1: Renewable energy share in the total final energy consumption.

Energy Conservation and Efficiency

- Target 7.3: By 2030, double the global rate of improvement in energy efficiency

Improvements in energy efficiency at all stages of the energy stream are a crucial part of achieving SDG 7. According to the IEA, improvements in energy efficiency provide various economic benefits, such as better resource management, higher industrial productivity, and stronger energy security; social benefits, such as improved health and wellbeing; and environmental benefits, such as reductions in greenhouse gas emissions. (IEA, 2014) Improving energy conservation and efficiency have been important agendas because the ROK's lacks of natural energy resources require existing energy sources to be used more efficiently. Thus, the country has put extensive efforts into improving energy conservation and efficiency for decades. To measure the progress of energy efficiency, the United Nations has selected energy intensity as an indicator. Primary energy intensity is "obtained by dividing total primary energy supply over gross domestic product." (UNSTATS, 2016)

International Cooperation to promote clean energy technology

- Target 7.A. By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency, and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology

Infrastructure and Technology for modern and sustainable energy services

- Target 7.B. By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support

In order to establish an index that presents the historical performance of the ROK's efforts in achieving SDG 7, a factor analysis was conducted. To examine the ROK's progress in achieving SDG 7, the selected data were used to run factor analysis and create an index due to limited data availability and applicability of specific indicators. The data used are the following: the proportion of the population with access to electricity, renewable energy share of total final energy consumption, energy intensity measured in terms of primary energy and GDP, and the amount of foreign direct investment in financial transfer for infrastructure and technology to sustainable development, the renewable energy share of total final energy consumption.

The weight of each indicator has been calculated as shown in Table 4-2. The weights of four indicators are as follows: Access to Electricity (26.88%); FDI on Utility (23.73%); Share of renewables (28.03%); and energy intensity (21.36%). The results imply that four major indicators have almost the same weights to derive the SDG 7 index for Korea.

Variable	Factor 1	Factor 2	Weight
Access to Electricity	0.9175	0.1196	26.88%
FDI on Utility	0.2653	0.8620	23.73%
Renewable	0.9368	-0.1372	28.03%
Energy Intensity	-0.3739	0.8178	21.36%

Table 4-2 Factor Loadings and Index Weight for SDD 7

The index created by factor analysis is shown in Figure 4-8 with the data from 1991 to 2020. The index presents a clear upward trend. This result indicates that the SDG 7 in ROK has continuously improved since 1980. The increasing trend of access to electricity and the improvement in energy intensity led to the improvement of the SDG 7 index. In the late 1990s, the progress of access to electricity, which already reached over 95% in 1995, was slowed down, and the worsening of energy intensity, caused by the extreme depreciation in the exchange rate during the Asian financial crisis, slowed down the pace of increasing SDG 7 index. The introduction of the Renewable Portfolio Standard (RPS) in 2012 accelerated the share of renewables, which is an important explanatory variable, and led to the continuing increase of the SDG 7 index. Access to electricity in Korea is, however, reached 100% in 2012, indicating that the access to electricity cannot be improved upon further. It implies that ROK should consider more renewable sources as well as the improvement of energy intensity in order to improve the progress in achieving SDG 7 in the future.

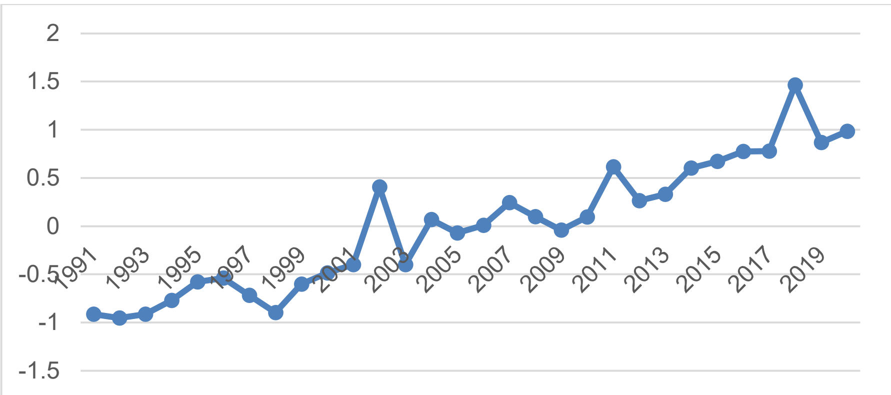


Figure 4-8 Index for SDG 7

References

Harman, H. H. 1976. *Modern Factor Analysis*. Chicago: University of Chicago Press.

http://www.energy.or.kr/renew_eng/new/standards.aspx/

Huang, W-H. 2015. The determinants of household electricity consumption in Taiwan: Evidence from quantile regression. *Energy* 87: 120-133.

International Energy Agency. 2014. *Capturing the multiple benefits of energy efficiency*. Paris: OECD/IEA. http://www.iea.org/publications/freepublications/publication/Captur_the_Multipl Benef_ofEnergyEficiency.pdf

Jung, T., Sustainable Development Goals in the Republic of Korea, edited book, Routledge, 2018.

Jung, T.; Kim, Y.; Moon, J. The Impact of Demographic Changes on CO2 Emission Profiles: Cases of East Asian Countries. *Sustainability*, 13, 677, doi:10.3390/su13020677, 2021.

Kim, C. H., and Park, G. S.. 2015. *The Analysis on the Determinants of Structural Changes of Electricity Consumption Pattern in Korea.* Korea Energy Economics Institute (Ulsan).

Kim, M-J. 2020. Understanding the determinants on household electricity consumption in Korea: OLS regression and quantile regression. *The Electricity Journal* 33 (7): 106802.

Korea Electric Power Corporation. 2021. Electricity Consumption by Contract Type.

Korea Energy Agency official site. *Renewable Portfolio Standards(RPS).*

Korea Energy Economics Institute and Korea Energy Agency. 2017. *2017 Energy Consumption Survey*, Ministry of Trade, Industry and Energy

Korea Energy Economics Institute, Korea Energy Statistical Information System, 2021.

Korea Meteorological Administration. 2020. *Korean Climate Change Assessment Report 2020: Summary for Policymakers*. Seoul: Korea Meteorological Administration.

Korea National Climate Data Center. 2021. Data collected by Automated Surface Observing System.

Lee, M.J., Lee, D.K., Park, C., Park, J.H., Jung, T.Y., Kim, S.K., and Hong, S.C. 2015. Prediction of Heating and Cooling Energy Consumption in Residential Sector Considering Climate Change and Socio-Economic. *Journal of*

Environmental Impact Assessment, *24*(5), 487-498.

McLoughlin, F, Duffy, A., and Conlon, M. 2012. Characterising domestic electricity consumption patterns by dwelling and occupant socio-economic variables: An Irish case study. *Energy and buildings* 48: 240-248.

Moon, J. 2022. An Analysis on Sustainable Electricity Supply and Demand in Korea with Application of Machine Learning Techniques (Doctoral dissertation). Yonsei University: Seoul, Republic of Korea.

Noh, S.C., and Lee, H.Y. 2013. An Analysis of the Factors Affecting the Energy Consumption of the Household in Korea. *Journal of the Korea Planning Association*, 48(2), 295-312.

Statistic Korea. 2021. E-local indicators.

Statistics Korea. 2011. *Population Prospects 2010-2060*. http://kostat.go.kr/portal/korea/kor_nw/1/2/6/index.board?bmode=read&aSeq=252623&pageNo=2&rowNum=10&amSeq=&sTarget=&sTxt=.

Statistics Korea. 2012. *Household Prospects (Provinces): 2010-2035*. http://kostat.go.kr/portal/korea/kor_nw/1/1/index.board?bmode=read&aSeq=259648&pageNo=221&rowNum=10&amSeq=&sTarget=title&sTxt=%EC%9D%B8%EA%B5%AC%EC%B6%94%EA%B3%84.

Statistics Korea. 2019a. *Household Prospects: 2017-2047*. http://kostat.go.kr/portal/korea/kor_nw/1/2/6/index.board?bmode=read&bSeq=&aSeq=377540&pageNo=1&rowNum=10&navCount=10&currPg=&searchInfo=&sTarget=title&sTxt=.

Statistics Korea. 2019b. *World and Korea Population Prospects 2019*. http://kostat.go.kr/portal/korea/kor_nw/1/2/6/index.board?bmode=read&bSeq=&aSeq=377226&pageNo=1&rowNum=10&navCount=10&currPg=&searchInfo=&sTarget=title&sTxt=.

Statistics Korea. 2019a. *Population Projections for Korea*, Korean Statistical Information Service "https://kosis.kr/statisticsList/statisticsListIndex.do?vwcd=MT_ZTITLE&menuId=M_01_01#content-group"

Statistics Korea. 2019b*. Household Projections, Korean Statistical Information Service* "https://kosis.kr/statisticsList/statisticsListIndex.do?vwcd=MT_ZTITLE&menuId=M_01_01#content-group"

Statistics Korea. 2020. *Statistics of single-person households in 2020*

UN General Assembly. 2015. “Resolution adopted by the General Assembly on 25 September 2015.” http://unctad.org/meetings/en/SessionalDocuments/ares70d1_en.pdf

United Nations Department of Economic and Social Affairs. 2010. *World Population Prospects 2010*. New York: United Nations.

United Nations Department of Economic and Social Affairs. 2019. *World Population Prospects 2019*. New York: United Nations. https://population.un.org/wpp/Download/Standard/Population/.

UNSTATS. 2016. “Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all.” https://unstats.un.org/sdgs/files/metadata-compilation/Metadata-Goal-7.pdf

Won, D. H. 2012. The Impact of Population Aging on Residential Energy Demand: The Electricity Case. *Environmental and Resource Economics Review*, 21(2), 341-369.

EDITS (Energy Demand Changes Induced by Technological and Social Innovations) Project

A research project of the

Institute of Innovative Technology for the Earth (RITE) – Japan

Report 2

By the Universidade Federal do Rio de Janeiro, Fundação COPPETEC – Brazil

Impacts of materials demand growth in energy transition scenarios

Rio de Janeiro, RJ – Brazil

February 2022

Impacts of materials demand growth in energy transition scenarios

Letícia Magalar[a], Marianne Zanon Zotin[a], Eduardo Müller-Casseres[a], and Roberto Schaeffer[a]

[a]Energy Planning Program, Graduate School of Engineering, Universidade Federal do Rio de Janeiro, Centro de Tecnologia, Bloco C, Sala 211, Cidade Universitária, Ilha do Fundão, 21941-972 Rio de Janeiro, RJ, Brazil.

Impacts of materials demand growth in energy transition scenarios

ABSTRACT

Mitigation options depend on technologies that require energy and materials throughout their life cycle. Thus, considering the energy transition underway, assessing its impacts throughout its production chain on the environment and society becomes crucial. Integrated assessment models (IAMs) have limited representation of industry and of materials, though industrial energy- and process-related CO_2 emissions were responsible for 25% of global emissions in 2020.
In this sense, the present work aims at reporting on the ongoing work of creating material representativeness in the COFFEE-TEA global IAM and demonstrate possible results that can be obtained from a more detailed analysis of material consumption. It also proposes an initial discussion on the possible unaccounted CO_2 emissions caused by the increase in materials demand. To achieve these objectives, a disaggregation the COFFEE industrial sector is required and the improvement of their technological pathways in parallel with the development of materials flows.
Thereby, it will become possible to assess potential constraints (e.g., overlooked increment in energy use and emissions associated with materials production) and opportunities (e.g., non-energy use of bio-based feedstock, potentially storing atmospheric carbon in bulk materials) in energy transition pathways. Results show that there is a very rapid expansion of renewable energy technologies under climate policy scenarios. And with this, there is a significant increase in the demand for cement and steel, which can be intensified by restrictions in exceeding the carbon budget. Finally, a significant increase in carbon emissions from the iron ore trade was also seen. Indicating the potential indirect impacts of increased demand for materials in other sectors than iron ore.

1. INTRODUCTION

Several decarbonization scenarios proposed by IAMs have focused mainly on changes in the energy supply side, which hinges on a wide penetration of renewable technologies along with carbon dioxide removal (CDR) technologies (Rogelj et al. 2018; Holz et al. 2018; Van Vuuren et al. 2018). However, despite being imperative, green energy technologies are more mineral intensive than fossil-based technologies (He, Zhong, and Huang 2021). In addition, mitigation measures in transition scenarios also include the electrification of energy end-use sectors, which will further increase materials demand and, consequently, the energy required from industrial processes and the carbon emissions from international maritime transportation (Fishman et al. 2021).
These advances in low carbon technologies may put pressure on several industrial sectors, which will potentially lead to an increase in demand and consequently force industries to further reduce GHG emissions. For this reason, it is crucial to understand how industrial subsectors can tackle a potential increase in production without penalizing their greenhouse gas reduction targets.
From infrastructure to fertilizers and plastics, these industries provide materials which are both essential for modern life which and hard to substitute in performance and cost. Combined with the scale of production globally and the capital-intensive and long-lasting equipment, they represent hard-to-abate sectors and a challenge to achieve stringent climate targets.

In 2020, the industry sector responded for 8.5 Gt CO_2 emissions – both energy- and process-related emissions – globally, which corresponds to around 25% of global direct CO_2 (Kermeli et al. 2021). Heavy industry – i.e., cement, steel, and chemicals sectors – contributes to 60% and 70% of industrial energy consumption and CO_2 emissions, respectively, because of high-temperature heat requirements (e.g., blast furnaces and cement kilns), non-energy use of fossil fuels (e.g., steam crackers), and process emissions (e.g., limestone calcination for clinker production). While such energy services are not easily electrified or substituted by biomass, it is still uncertain whether carbon capture and storage (CCS) will be a feasible alternative for CO_2 emissions-intensive activities.

The level of detail in industrial sector representation in global process based IAMs is limited (Sluisveld et al. 2021). A lot of effort has been given to industrial sub-sectoral disaggregation in IAMs in recent years, mostly to cement and iron and steel industries (Edelenbosch et al. 2017; Ruijven et al. 2016; Sluisveld et al. 2021)

Kermeli et al. (2019) incorporated mitigation measures specific to the cement sector in the integrated evaluation model IMAGE. They are retrofit and reduction of clinker to cement ratio. These measures resulted in significant reductions in energy demand, mainly in mitigation scenarios. However, these results are directly linked to steel and electric power industries as they are both responsible for supplementary cementitious' materials availability, which highlights the necessity to link different industries in IAMs. (Kermeli et al. 2019)

Oliveira et al. (2020) recently took a step to better understand the role of polymers in the energy transition by representing the supply chains of basic petrochemicals (ethylene, propylene, butadiene, and a mixture of benzene, toluene, and xylenes) and its bio-based counterparts to the Brazilian IAM (BLUES).

Van Sluisveld et al. (2021) assessed the role of decarbonizing the heavy industry (i.e., iron & steel, clinker & cement, chemicals and pulp & paper) in achieving global net-zero carbon emissions by 2050 and decarbonisation patterns were found to be industry and regionally specific.

However, these efforts are still insufficient to grasp how organic and inorganic bulk materials production in hard-to-abate sectors can become constraints and/or opportunities to deep decarbonization pathways.

In this sense, the refinement of the industrial sector in IAMs enables the evaluation of possible measures that different industries can adopt to cope with fluctuations in demand imposed by transition scenarios.

Inasmuch as materials are the result of industry processes, estimating the material needed to drive a low-carbon economy paves the way for further research to better comprehend how industries should develop and how materials can contribute to their decarbonization.

The materials are also highly relevant for tackling climate change. They contribute to almost 25% of total global greenhouse gas (GHG) emissions (Hertwich et al., 2019), and bulk materials tend to continue to grow in the coming decades due to their consumption being directly linked to income and population growth, mainly in developing countries (WB 2016) This fact alone poses a challenge for decarbonization, which is to decouple material demand from population and income while respecting sustainable development goals. By including the materials required for the energy transition, the industry decarbonization pathway becomes even more challenging.

Some studies have evaluated materials demand using IAMs. Zhang et al. (2019) incorporated materials and water intensity into the Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGEix) for China's iron and steel industry. The authors identified synergies between raw materials, consumption of scrap, energy, and water and CO2 emissions to identify which processes and technological routes are the most energy and materials efficient.

While Deetman et al. (2019) and Marivona et al. (2020) focused on the in-use stock of bulk materials in residential and service buildings towards 2050 by converting material intensities per square metre into material stock using the total useful floor area specified for 26 world regions, as projected by the IMAGE model. Lastly, Deetman et al. (2021) focused on answer how the global material stocks and flows related to the electricity sector may develop towards 2050 considering climate policy scenarios derived from the IMAGE model (Marinova et al. 2020; S. Deetman et al. 2021; Sebastiaan Deetman et al. 2020; Habib, Hansdóttir, and Habib 2020).

IAMs can model several potential paths to achieve the objectives of the Paris agreement. However, only a few evaluate the influence of materials on the feasibility of low carbon scenarios. Most of the above-mentioned studies demonstrate the scientific community's efforts to better represent industry in IAMs and incorporate material flows and restrictions in IAMs. However, materials modeling in energy systems still have a long way ahead since most of the articles are restricted to analyzing only a limited number of industries and usually separated from each other. In other words, efforts are still needed to integrate materials flows across all sectors considered in IAMs.

For this reason, this study has a threefold objective. Firstly, it aims to further improve industrial representation in the COFFEE-TEA model by including the cement, iron and steel, and chemicals sectors in the modeling framework.

Secondly, the study contributes to the development of the materials satellite model (MATE) that will be exogenously linked to COFFEE model, establishing a methodology for calculating the materials demand in the energy and transportation sectors under more stringent climate scenarios.

And lastly, it highlights whether decarbonization scenarios can intensify CO_2 emissions from international maritime trade because of greater demand for materials in low carbon scenarios.

This paper is organized into 5 sections. In this first, we review the importance of considering the material sphere in IAM models and what has been done in the scientific community so far. The second section shows the methodologies applied to improve the COFFEE industrial sector and to include a material analysis in the model. The third section describes the main results for cement and steel demand in energy sector due to different climate policy assumptions, as well as the COFFEE results for the steel and cement industry. The fourth section provides a discussion regarding the possible repercussions of the results obtained and finally the fifth section summarizes the main objectives and results of this ongoing work.

2. METHODS

2.1. MATERIALS DEMAND IN TRANSITION SCENARIOS

The methodology proposed to determine the material demand for the energy generation and transmission subsectors is illustrated in Figure 1. The cement and steel demand are calculated considering the increment capacity of energy generation technologies forecasted in each climate demand scenario until 2100 multiplied by a coefficient of material weight by capacity installed in a given period.

The energy generation technologies considered are hydroelectric, CSP, PV, wind onshore, wind offshore, geothermal, and thermoelectric with biomass, oil, coal or natural gas sources with or without CCS. It should be noted that the pipeline infrastructure associated with CO_2 transportation is beyond the scope of this work.

Specifically for the energy transmission and distribution subsectors, a transmission line length coefficient per installed capacity was calculated based on regional historical data. Next, this coefficient was applied to the results of future installed capacity of COFFEE, resulting in grid line length per period. With these results, it is possible to estimate the number of transformers and substations needed to apply material intensity coefficients to estimate materials demand.

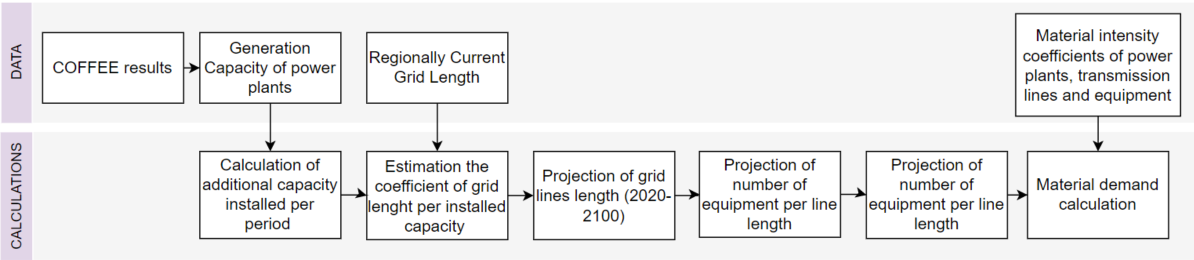


Figure 1: Methodology Flowchart

This work gathered capacity installed data from five climatic scenarios that stem from the COFFEE model. The baseline scenario considers no restrictive policies on carbon emissions, and therefore, it is the scenario that presents the highest concentration of CO_2 by the end of the century. Differently, the other four scenarios consider current national climate policies implemented by countries worldwide plus carbon budget and overshooting restrictions. Two scenarios consider a carbon budget restriction of 400 Gt, but in one overshooting is not permitted (Budget 400), whereas the other allows CO_2 emissions to be exceeded as long as the stipulated budget limit can be reached by 2100 (Budget 400 OS). The other two scenarios follow the same rationale differing only in budget amount. They are Budget 800 and Budget 800 OS.

The following subsections detail the considerations and calculations used for this work.

2.1.1. MATERIALS DEMAND FROM THE ENERGY GENERATION SUBSECTOR

Prior to commencing material demand calculations, it is necessary to create a database of material demand by type of electricity generation technology which is presented in Table 1.

The database was developed through material intensity coefficients found in the available literature whenever possible. The ecoinvent database (Vandepaer et al. n.d.) was consulted for missing data and specific considerations regarding each technology process, which are detailed in ANNEX 1.

Exclusively for cement demand, it was necessary to estimate the material intensity coefficient using the data obtained for concrete consumption. For this, average values were used for concrete's density[1], which directly depends on the percentage of cement, sand, aggregates, and water. The amount of cement used in concrete may also vary depending on its application purpose.

[1] According to Wernet et al. (2016) concrete density can vary between 1.2 to 2.5 t/m3 and cement-to-concrete ratio range adopted were 273 – 306 kg cement/m3 concrete

The available installed capacity data consider the accumulated installed capacity. Thus, it was necessary to calculate the additional installed capacity required in each period between 2020 and 2100 with time intervals every ten years. It is important to note that no replacement of decommissioned plants was performed because considerations regarding power plant decommissioning are already done endogenously in each IAMs.

Once all additional capacities are defined, it was possible to calculate material demand for each scenario and IAM based on the following equation:

$$D_{x,t} = \sum_{t} (Cap_{t,s} - Cap_{t-1,s}) \times \beta_{x,s}$$

Equation 1

Where:

Dx,t is the demand of a particular material x in period t

Cap_t is the additional capacity of a given technology s in each period t

bx,s is the material x intensity of a given technology s

A consideration has been made regarding the use of scrap in steel industry to reduce the demand for primary steel. Thus, for this work, it was considered that the market share of electric arc furnace (EAF) technology (Worldsteel 2013; 2020) is equivalent to the percentage of scrap used for the energy sector in each period. This is because this technology is capable of processing secondary steel. Moreover, it was observed in the literature that this percentage is lower than the estimated availability of secondary steel derived from material flow analysis modelling (Pauliuk 2017).

2.1.1. MATERIALS DEMAND FROM THE ENERGY TRANSMISSION AND DISTRIBUTION SUBSECTOR

The first step in calculating the length of transmission lines is to determine a coefficient that allows estimating the grid length from the energy converters' installed capacity data. For this, it was necessary to obtain data on all energy generation sources' installed capacity for 2015 for each scenario. The calculation for high voltage (HV) line length was based on and **Error! Reference source not found.** as follows (Deetman et al. 2021):

$$\boldsymbol{AHV_{rt} = HV_{r,t} - HV_{r,t-1} + HV_{out,r,t}}$$

Equation 2

$$\boldsymbol{HV_{r,t} = RECap_{r,t} \times \frac{HV_{base,r}}{Cap_{base,r}}}$$

Equation 3

Where:

$\boldsymbol{AHV_{rt}}$ is the HV additional line in region *r* in period;

$\boldsymbol{HV_{r,t}}$ is the HV line in region *r* in period *t*;

$\boldsymbol{HV_{r,t-1}}$ is the HV line in region *r* in period *t-1;*

$\boldsymbol{HV_{out,r,t}}$ is the HV length necessary to replace old lines in region *r* in period *t;*

$\boldsymbol{RECap_{r,i}}$ is the additional capacity installed of wind and solar sources in period *t;*

$\boldsymbol{HV_{r,base}}$ is the HV length in a given region in 2015;

$\boldsymbol{Cap_{r,base}}$ is the total electricity generation installed capacity in region *r*, in 2015

The length of medium voltage (MV) and low voltage (LV) lines were estimated using a ratio related to HV length extracted from (Arderne et al. 2020). The additional transmission line projection for each period and region considered its lifetime as 40 years. In the absence of historical data on grid length, it was presumed that all new lines and equipment were implemented in 2015.

Once all line lengths have been estimated, a ratio of the transformers and substations units per line length is used to estimate the number of auxiliary equipment required by period and by region.

The materials considered in this work cement and steel. For the calculation of materials demand for each scenario, this study used material weight coefficients per line length or number of equipment as follows:

$$\boldsymbol{D_{x,t} = L_t \times \beta_x} \tag{4}$$

$$\boldsymbol{D_{x,r,t} = Eq_{r,t} \times \beta_x} \tag{5}$$

Where:

$\boldsymbol{D_{x,t}}$ is the material *x* demand in Mt in period *t*;

$\boldsymbol{L_t}$ is the HV, MV, and LV line length in period *t*;

$\boldsymbol{Eq_{r,t}}$ is the number of transformers and substations in period *t*;

$\boldsymbol{\partial_x}$ is the material *x* intensity coefficient

2.2. INDUSTRIAL SECTOR IMPROVEMENTS IN THE COFFEE MODEL

The COFFEE model is based on linear programming optimization, minimizing simultaneously the total costs of the completely hard linked energy and land-use systems as energy services and materials (physical) demands are fulfilled (IAMC, 2020).

To improve the industrial sector representation in the COFFEE-TEA model, we incorporated technological routes to fulfill cement and steel demand from 2010 to 2100. Technological routes based on electrification/hydrogen, biomass (for energy and reducing agent in blast furnaces) and CCUS were included in each sector, as well as energy efficient alternatives for traditional technologies, to offer the model different technological and energy resource possibilities to fulfill regional long-term demands as cost-effectively as possible under different climate scenarios. Figure 1 illustrate the non-energy use of fuels (e.g., reductants in iron and steel industry and carbon feedstock for chemical production), the technologies and products in each of the sub-sectors included.

The first step was to exogenously calculate the regional demands for cement and steel. For this, projections from 2010 to 2100 were estimated based on historical data on economy-wide socioeconomic and demographic drivers (GDP, GDP/capita and kg/capita) under SSP2 assumptions. It is worth noting that material demands were based on historical data, and therefore they don't yet consider possible increments related to a more significant penetration of low-carbon technologies worldwide. Regional apparent steel and cement consumption data from 2003 to 2019 was retrieved from World Steel Statistical Yearbooks (Worldsteel 2013; 2020) and from the USGS database (USGS 2013; 2017), respectively.

The technological portfolio in the cement sector includes dry, energy efficient dry, wet, dry with CCS technologies as well as measures to reduce the clinker to cement ratio beyond regional historical patterns. As for the steel sector, blast furnace integrated to basic oxygen furnaces were modelled – both using coal and charcoal as reducing agents – as well as the production of direct reduced iron (using both natural gas and hydrogen) and the recovery of steel scrap to feed electric arc furnaces. A variation of the former was also included to represent methanol production from coke oven gas in China as a co-product in integrated steel plants. Also, smelting reduction and open-hearth furnaces were included in the analysis as well as all technologies combined with CCS, whenever possible.

Process technologies parameters – such as investment costs, operating and maintenance costs, final energy inputs, process yields, first time of technology availability and plant lifetime – were collected for the cement (GCCA, 2019; Kermeli et al., 2019; Lerede et al., 2021; Rissman et al., 2020; Van Ruijven et al., 2016) and steel (Di Cecca et al., 2016; IEA, 2020, 2019b; Lerede et al., 2021; VAI, 2011; Worrell et al., 2010) sectors from a vast literature.

These processes were modeled and hard-linked to the COFFEE model framework (Rochedo 2016). Long term evolution of fuel use and technological portfolio were evaluated regional and globally under carbon pricing shocks of $10, $50, $100 per tCO2 for the time horizon for 2020 to 2050.

2.3. IMPLICATIONS FOR INTERNATIONAL TRADE

The impact of varying material demand on international trade is also modelled. Materials and minerals figure among the main cargoes of international shipping. As such, a higher demand for products such as steel and cement can have significant impacts on shipping activity. In this context, iron ore stands out as the most important maritime cargo. Therefore, in this study, the global iron ore market is selected as a case study of potential increases in shipping activity associated with material demand.

As shown in Table 1, currently, the international seaborne trade of iron ore (~1.5 Gt/year) is focused on a few routes involving two main exporters, Australia and Brazil. The two countries account for more than 75% of the iron ore exports. The main importing regions are Asia Pacific and Europe.

Table 1: Iron ore shipping routes and associated trade flows between 2016 and 2020

SHIPPING ROUTES		Iron ore trade flows (million tonnes)				
Exporting country	**Importing region**	**2016**	**2017**	**2018**	**2019**	**2020**
Australia	Asia Pacific	811	829	839	840	873
Brazil	Asia Pacific	286	286	285	266	293
Brazil	Europe	52	49	46	34	24
Brazil	Other	36	49	58	41	25
South Africa	Asia Pacific	49	51	47	48	50
South Africa	Other	16	16	16	18	15
Canada	Asia Pacific	17	18	20	23	29
Canada	Europe	19	20	22	22	20
Canada	Other	41	43	48	52	55
Other	Other	179	195	205	193	246

To analyze the impacts of a higher steel demand on dry bulk shipping energy and CO_2 emissions, a simplified analysis based on the routes of Table 1 was performed. Using the results for material demand from section 2.1.1 and the historic trade values from Table 1, trade volume projections were created for 2030, 2050 and 2100. To that end, a few assumptions were adopted:

- The activity of iron ore exporting routes is assumed to be bounded to the steel consumption of importing regions. As such, the iron imports of a certain region are proportional to the steel consumption of the same region.
- For importing regions, the share of each exporting country is assumed to be constant, equal to the average share of the period 2016-2020. For example, in 2030, 2050 and 2100, 70% of the Asia Pacific iron ore imports are assumed to come from Australia, 24% from Brazil, 4% from South Africa and 2% from Canada.

The average haul for each route is defined according to major ports of exporting countries and importing regions, as shown in Table 2. For unspecified regions, an average haul of 5,000 nm is used.

Table 2: Iron ore shipping routes, representative ports and average haul

Exporting country	Importing region	Exporting port	Importing port	Average haul (nm)
Australia	Asia Pacific	Port Hedland	Qingdao	4,059
Brazil	Asia Pacific	Tubarão/Ponta da Madeira	Qingdao	14,154
Brazil	Europe	Tubarão/Ponta da Madeira	Rotterdam	5,882
Brazil	Other	-	-	5,000
South Africa	Asia Pacific	Saldanha	Qingdao	9,741
South Africa	Other	-	-	5,000
Canada	Asia Pacific	Sept-Îles	Qingdao	14,354
Canada	Europe	Sept-Îles	Rotterdam	2,931
Canada	Other	-	-	5,000
Other	Other	-	-	5,000

The vessels associated with the ten shipping routes are shown in Table 3. In general, the iron ore market uses Capesize ships. Brazilian exports use both Capesize and Valemax ships. In the current modelling, Valemax ships are assigned to Brazilian exports while Capesize ships are assigned to the remaining routes. Conservative energy efficiency assumptions are adopted: the ships energy intensity is assumed to decrease 7% by 2030, 15% by 2050 and 30% by 2100.

Table 3: Vessels used in the shipping routes

Exporting country	Deadweight (dwt)	Energy intensity (MJ/t-nm)
Capesize	180,000	1.69
Valemax	350,000	1.50

3. RESULTS

3.1. CEMENT AND STEEL DEMAND

Before examining the cement and steel demand, it is important to comprehend how the additional capacity required for energy generation may vary in each scenario. This is because even though the demand for energy is the same, there is a straight relationship between the variation of the installed capacity and the share of renewable energy plants in the energy matrix due to their intermittent nature.

Figure 2 depicts the additional capacity of power plants in baseline scenario. As can be seem, there is a relevant share of wind onshore plants by 2050 and an increase in coal plants as well. The increase in installed capacity from 2070 onwards also portrays the replacement of power generation plants that have been decommissioned and partially substituted by wind power plants as the model starts to prefer due to their reduced cost over time.

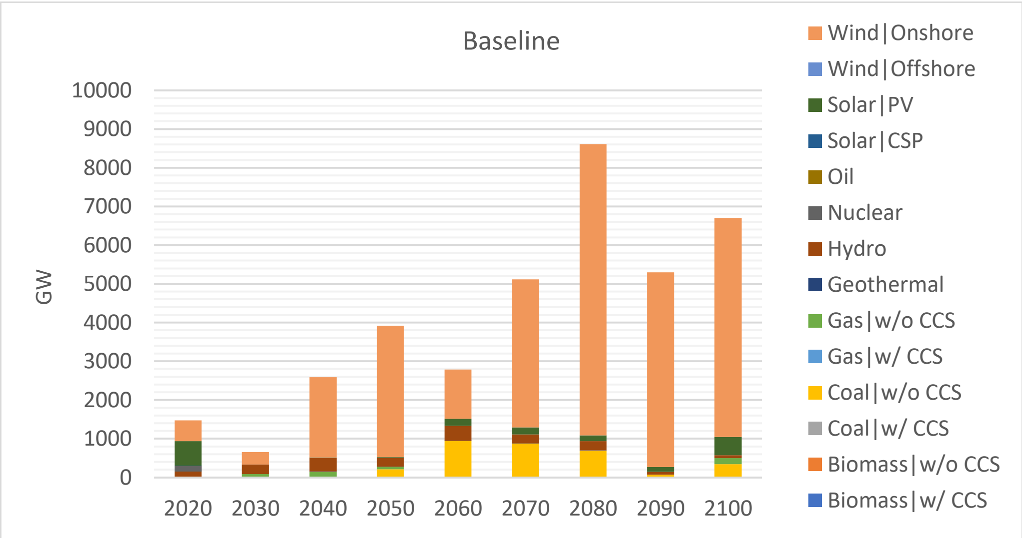


Figure 2: Additional capacity installed of energy generation plants in Baseline scenario

In Figure 3 shows the additional capacity of power plants in policy scenarios by scenario and period. It shows that in more restrictive scenarios, in which delayed decarbonization is not allowed, there is a sharply growth of renewable energy installation in the next decade. And this increase is directly related to the intensity of the carbon budget restriction.

Figure 3: Additional capacity installed of energy generation plants in Policy scenarios

This is an expected outcome for energy planning experts. However, a non-trivial result arises when observing the cumulative additional capacity until the end of the century. Figure 4 reveals that even though the scenarios without overshooting permission must accelerate investment in renewables, late decarbonization (overshooting scenarios) actions may end up requiring more capacity installed, which is likely to demand an even larger amount of materials in the second half of the century.

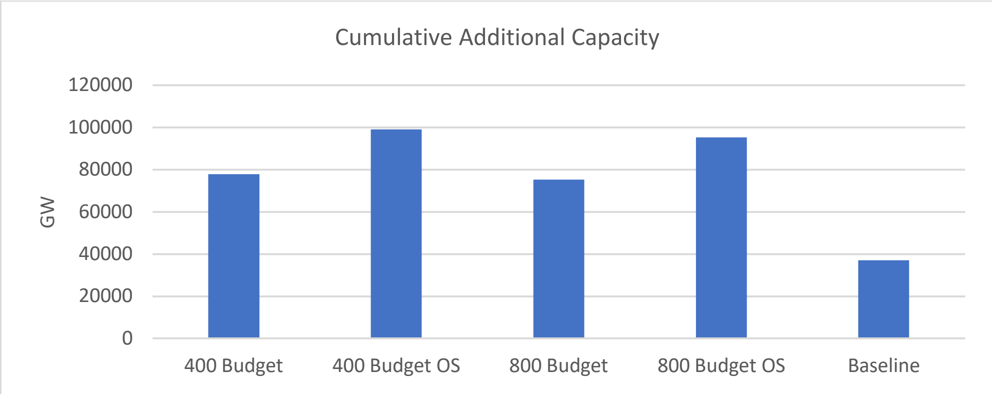


Figure 4: Cumulative additional capacity installed per scenario

The future requirement for cement and steel can vary greatly depending on the assumptions taken on energy generation technologies. Renewable technologies such as hydro power, especially those with reservoirs, and wind power rely heavily on concrete and therefore, cement.

Figure 5 shows the demand for cement in the baseline scenario. As can be seen the demand for cement for the energy sector grows steadily with a small increase in 2080 pushed mainly by wind onshore and hydro plants.

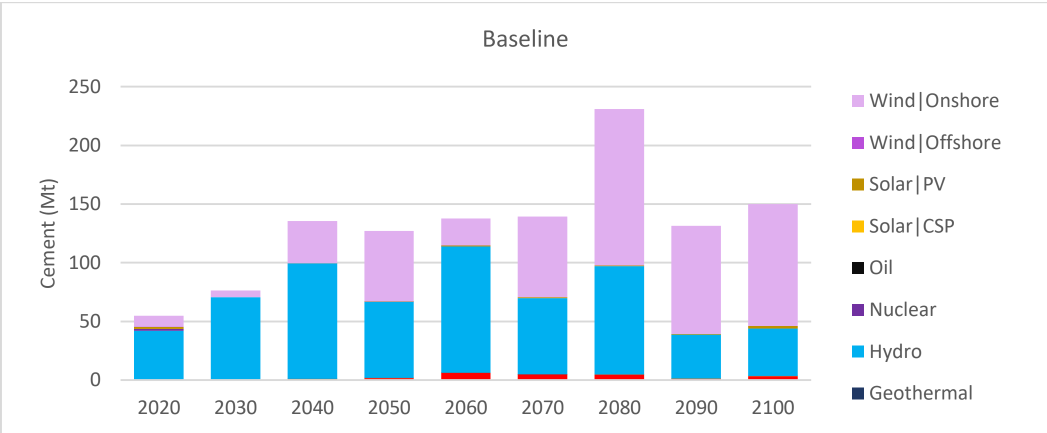


Figure 5:Cement demand in baseline scenario

Looking at **Figure 6**, it is apparent that climate policies scenarios also follow the behavior described at the beginning of this section. However, some demand behaviors are observed by reason of differences in climate policies considered.

The Budget 400 scenario has a sharp growth in cement demand in 2030 due to the impossibility of exceeding the carbon budget that has been set. Although hydropower plants represent only 10% of the total installed capacity, it is the technology with the highest cement intensity, which explains the greater amount of cement coming from this technology.

In the Budget 400 OS scenario, even though there is the same restriction in the carbon budget, because the emission limit is imposed only in 2100, it allows renewable technologies penetration to be implemented with a more stable growth, with a peak in demand occurring in 2060. Biomass power plants without CCS contributed about 1% of the demand during all periods and the same percentage occurred with coal-fired thermoelectric with CCS.

The Budget 800 scenario follows a similar behavior as the Budget 400 OS scenario in terms of the amount of additional installed capacity per period. However, there is a slightly greater share of renewables that are expected to be installed in the coming decades. Finally, the Budget 800 OS scenario also presents a similar behavior to the Budget 400 OS scenario, however it presents a more accentuated demand for cement and steel in 2070.

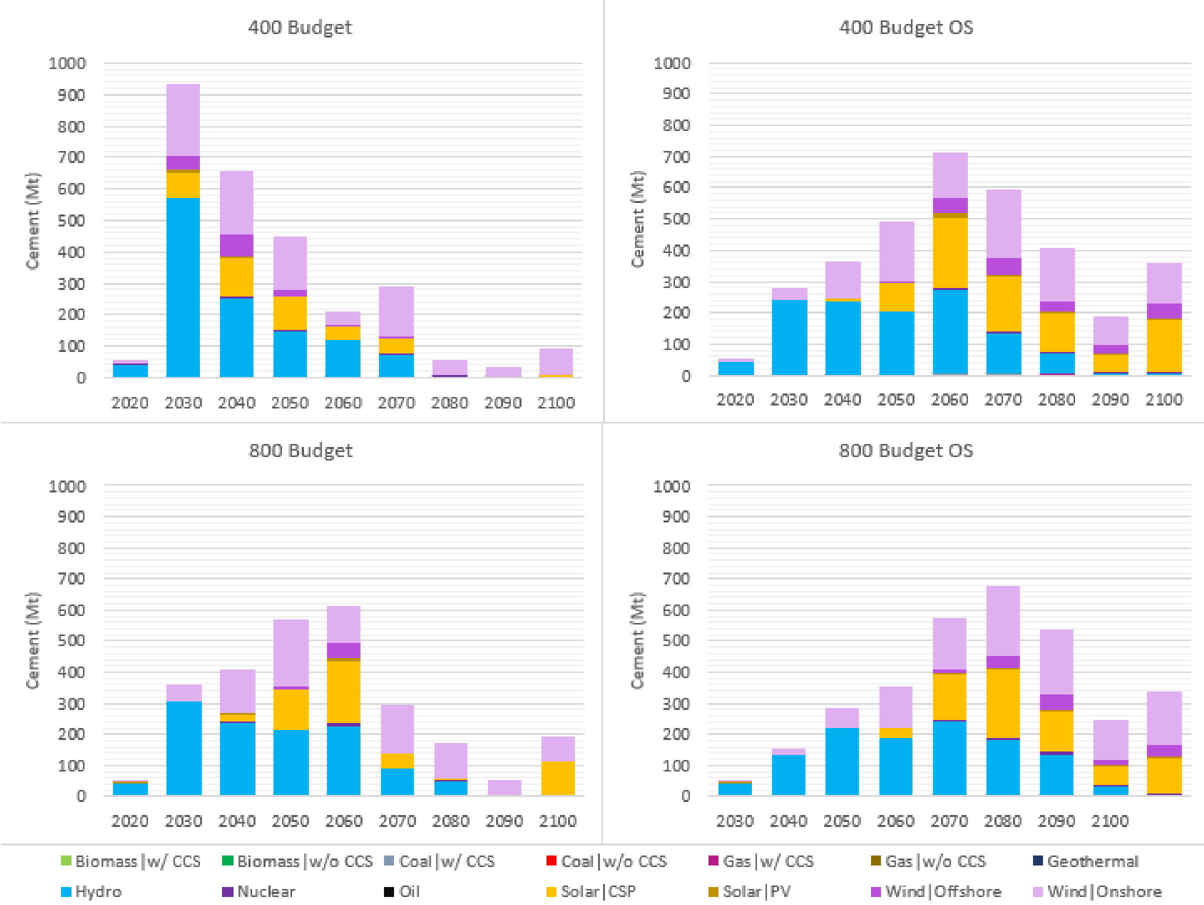


Figure 6: Cement demand in policy scenarios

Figure 7 presents steel demand in the baseline scenario. Onshore wind power continues to play a key role in the energy transition, and this leads it to be responsible for the increased demand for materials. However, when looking specifically at steel demand, there is also the presence of coal-fired thermal power plants that have their capacity increased mainly during the second half of the century.

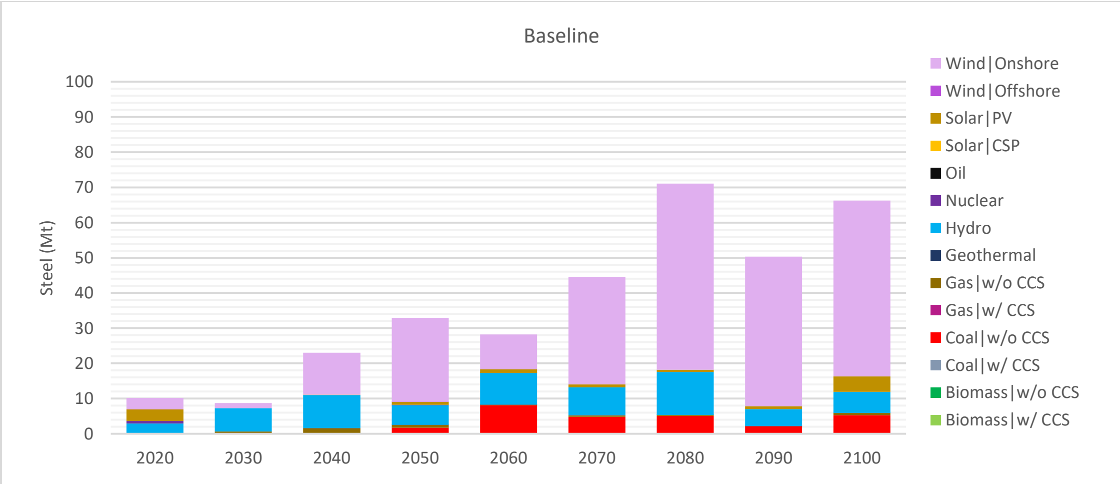


Figure 7: Steel demand in baseline scenario

The demand found for steel also behaves in a similar way to the demand for cement. That is, in the 400 Budget scenario without overshooting, steel use grew steeply in 2030 and decreased at a slower pace in the following decades (**Figure 8**). But differently from the cement results, wind and solar power plants correspond to more than 60% of the demand for steel, and this percentage is even higher throughout the periods for all scenarios.

Regarding the thermoelectric plants, in the Budget 400 and Budget 800 scenarios there is a small participation of a little more than 1% of coal thermoelectric plants with carbon capture from 2030 on. And the biomass thermoelectric plants without capture are included in the global energy matrix only after 2050 and do not exceed the share of 2% of total steel demand.

In the Budget 400 OS and Budget 800 OS scenario, coal-fired plants with CCS become 2% of the energy matrix and gas-fired plants with CCS have a participation of 1% from 2050 onwards. Finally, nuclear power had in all scenarios a share of steel demand of between 3% and 6%.

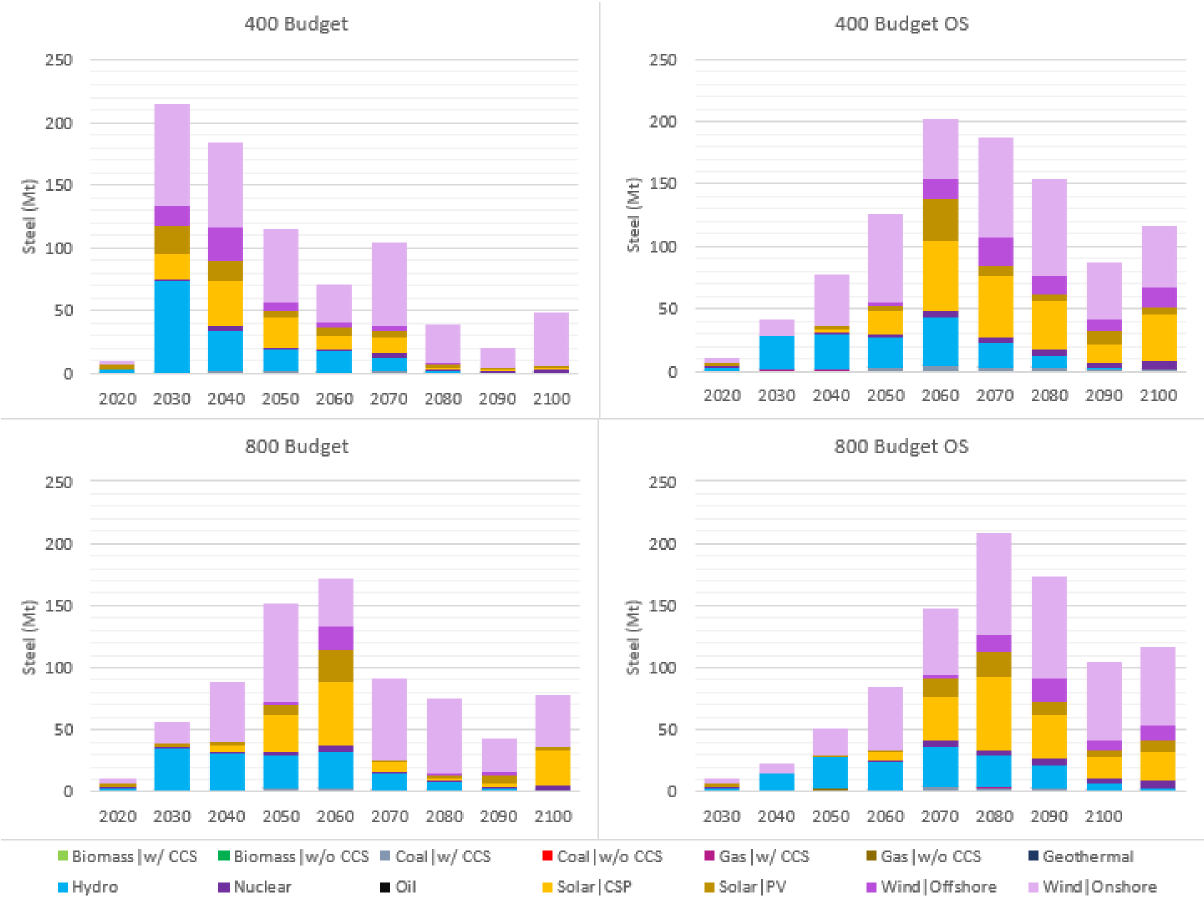


Figure 8: Steel demand in policy scenarios

3.2. Cement and steel pathways in carbon pricing scenarios

Global cement and steel demand raises from about 3290 Mt and 1775 Mt in 2020 to 4381 Mt and 2650 Mt in 2050, respectively, following historical patterns of GDP and material consumption per capita (Figure 9 and Figure 10). China is responsible for a substantial share of both materials through the next decades. However, while its demand for cement gradually decreases, its demand for steel increases to reach its peak in 2040.

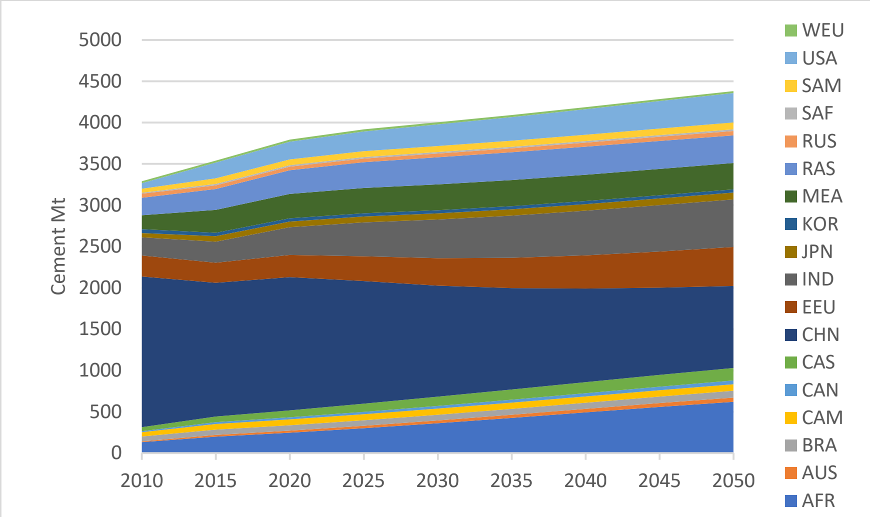


Figure 9: Cement demand considered in COFFEE

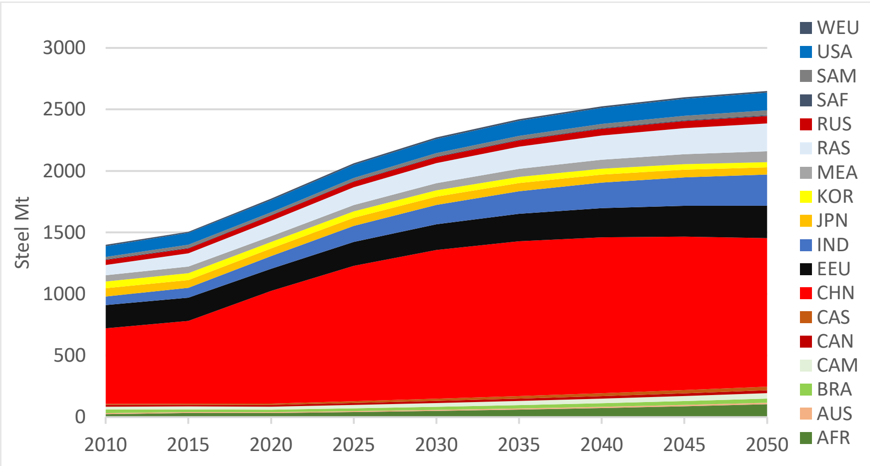


Figure 10: Steel demand considered in COFFEE

Future projections of the global industrial technology pathways under different carbon prices - representing climate policies throughout the integrated systems – were drawn from the optimized solution of the COFFEE model.

For the cement sector, as carbon prices raises, CCS becomes increasingly relevant, and coal dramatically reduces its share in heat generation (Figure 11). It makes room for natural gas, coal with CCS and biomass with CCS to deliver the heat requirements of the sector. As for the global clinker to cement ratio, it gradually decreases to 70 and 68% through the period.

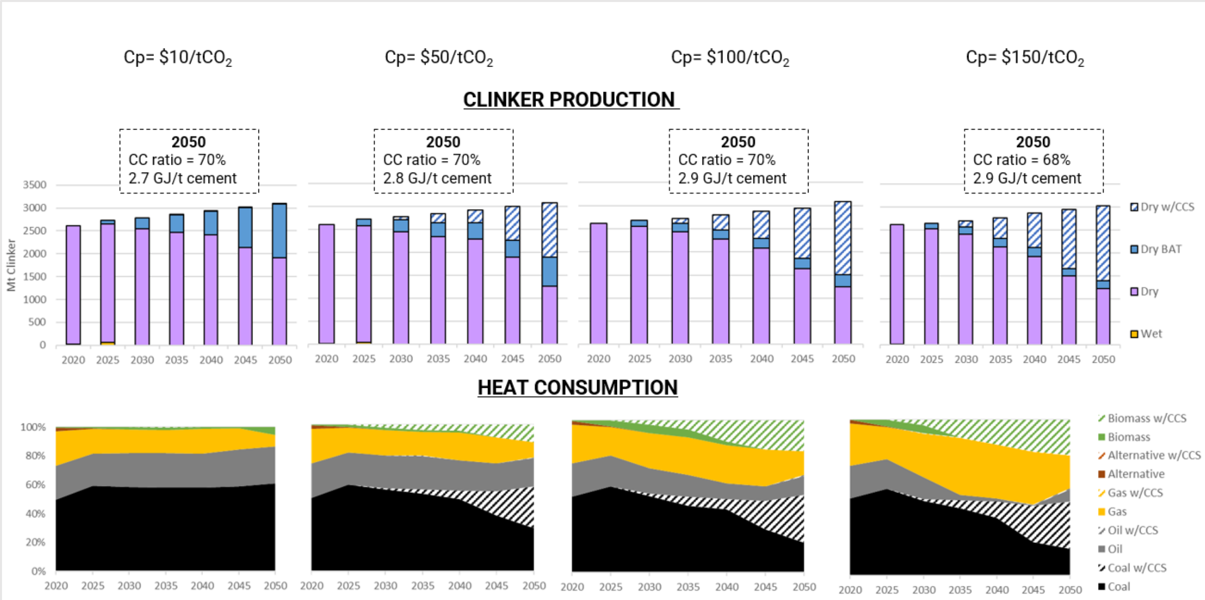


Figure 11: COFFEE results for clinker production

In the iron and steel sector, energy intensity declines in all scenarios, reaching around 10-11 GJ/t steel in carbon prices of \$100/tCO_2 (Figure 12). Also, in lower carbon prices, process efficiency is preferable in whereas in carbon prices of \$50/tCO_2 CCS technologies have a central role in mitigating the systems emissions. In the scenario with \$100/tCO_2, however, CCS and BOF technologies reduce their share while direct reduction (natural gas with and without CCS) as well as scrap recycling become more relevant.

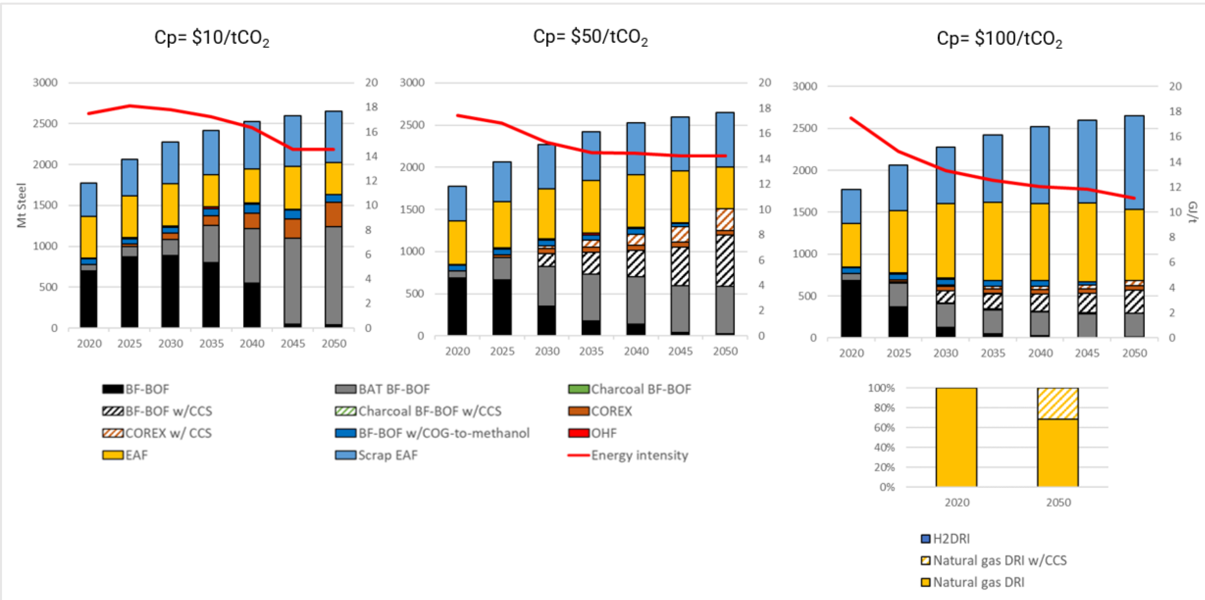
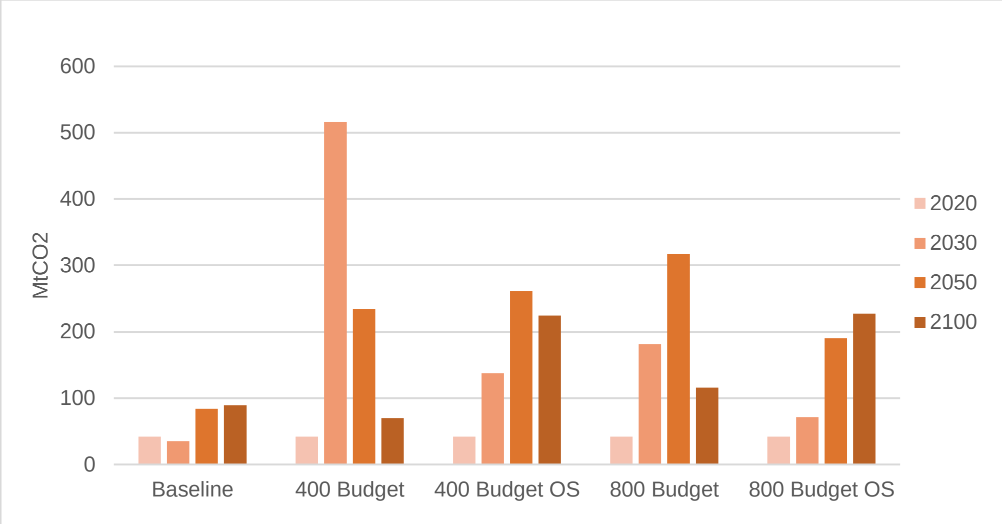


Figure 12: COFFEE results for the steel industry

3.3. IMPLICATIONS FOR INTERNATIONAL TRADE



-

Figure 13: Carbon emissions from iron ore trade

Figure 13 shows the carbon emissions from the iron ore trade, which supplies the steel chain. As can be seen there is a tendency for emissions to increase in all scenarios, however, as expected, they peak at different time periods due to greater or lesser restrictions on the carbon budget and whether overshooting is allowed.

4. DISCUSSION

A strong relationship between the urgent deployment of renewable energy capacity and the growing need for materials has been reported in the literature. However, only recently the research community began to investigate the potential impacts of increased demand for materials for the energy transition in CO_2 emissions and other related impacts (Deetman et al. 2021; Kermeli et al. 2021; Nong et al. 2020; Sluisveld et al. 2021).

The results found in this study reveal that mitigation policies for the global electric matrix can significantly contribute to increase materials use and consequently, could reduce the overall mitigation capacity due to unaccounted materials' carbon emissions.

In this study, we calculated potential cement and steel demand increments in the electricity sector (generation, transmission, and distribution). However, material requirements for other energy sectors were not included and should be further assessed. For example, many studies claim that, to maintain the global temperature below 2°C, climate policies will probably have to rely on carbon capture and storage technologies (CCS). Also, especially in the heavy industry sector, CCS technologies are key to decarbonization pathways, as seen in Figure 12.

A potential negative impact was identified concerning the further development of such technologies. Although the demand for steel and other materials needed for the carbon pipeline infrastructure is out of the scope of this report, the results presented here point to a need to evaluate the real capacity of carbon capture technologies to reduce emissions, since there have carbon emissions embodied in these technologies, resulting from the extraction and processing of materials which are rarely seen in IAMs.

Moreover, the development of new technologies capable of sequestering carbon as the overall increasing use of materials blurs several issues related to sustainable development objectives, particularly in developing and weak governance countries. For instance, the increase in materials usage relates to impacts of decent work, water, and food availability (de Selliers and Spataru 2018). The lack of end-of-life product management has severe impacts on the environment, such as the vast presence of plastics in the ocean. With these considerations, the more detailed representation of the materials in IAMs becomes even more relevant.

Another important point is the fact that these very sudden increases in materials requirement can cause a gap between supply and demand, driven by the industry's inability to meet an expansion in its production capacity so promptly. These events generally cause an oscillation in the price of materials and may end up redirecting the market to opt for carbon intensive technologies as an indirect effect. Therefore, the analysis of materials effects in energy transition will also allow climate policies to achieve a more systematic vision of the direct and indirect consequences caused by materials requirement.

In this sense, this study also draws attention to the need to adopt material efficiency policies in the industry as well as the development of policies that cause a change in consumer behavior.

When considering this trend, a fundamental analysis to be performed in future studies is to assess the impact of late actions on materials demand. It could lead to a skyrocketed consumption of materials in a short period, which may bring up supply restriction risks as well as economic, socio-environmental, and geopolitical concerns.

5. CONCLUSION

The objective of this ongoing study is twofold. Firstly, a methodology was developed to evaluate the demand for materials in different climate policy scenarios. It was calculated the cement and steel demand for energy generation and transmission sector by estimating the necessary grid expansion between 2020 and 2100 and further applying coefficients of material use per energy generation capacity, transmission line lengths and auxiliary equipment.

The second objective of this research was to improve the technological routes of the COFFEE model industrial sector. The improvements made in this work will enable further analysis to evaluate opportunities and constraints associated with higher material requirements in climate mitigation scenarios.
In addition, it will also open doors for the development of material interlinkages between other sectors represented in the model such as transport and buildings, and thus begin to endogenously assess the impacts of circular economy measures in COFFEE.

The third part of this paper was devoted to estimating the extent to which an increased demand for materials could impact international maritime trade. This analysis is important because this industry is known to be a difficult industry to shake. The most restrictive scenarios could even quadruple the emissions from this sector, considering only the iron ore flows, which represent only a portion of the flows that occur involving steel.

The findings of this work reveal a correlation between climate policy ambitions and renewable energy penetration rates. Thus, materials demand growth is directly related to carbon budget restrictions because the higher the carbon concentration restriction, the greater the expected renewable energy installed capacity.

This analysis, although simplified, is imperative because it generates important information for further studies on possible rebound effect in the industry as well as it can serve as an input parameter for econometric models to better represent material demand projections and production capacity restrictions in materials' supply change.

Regarding the industry technological and energy portfolio trajectories under carbon constrained scenarios, an increase in demand would further stress a high emitting and hard to abate sector. By underestimating carbon and energy intensive materials demand in IAMs, the strategies to achieve climate goals may be more challenging than anticipated.

However, materials demand for fossil fuel-based technologies – e.g., oil and gas pipelines, oil platforms – may also reduce. This reduction should be accounted for as well as the recycling potential and other material efficiency measures potential so as to capture a realistic range of hard-to-abate emissions in the next decades.

A critical limitation found in this work is that the transmission lines projection methodology did not consider regional particularities such as intensifying underground transmission lines or implementing interconnection projects between countries. Such aspects can directly impact the demand for grid infrastructure and materials demand.

Future studies should also include an assessment of the possible effects of materials substitution, reuse, and recycling. In addition, it is also necessary to understand how the material intensity coefficient can change over time due to circular economy strategies and technological developments.

Although the results should be interpreted with caution, this study has several strengths, such as pointing to the significant demand for materials due to the expansion of electricity transmission infrastructure, which is often neglected by other studies. And it also reinforces the hypothesis that scenarios with carbon emissions restrictions can sharply increase the demand for materials and intensify geopolitical, social, environmental, and economic issues in different countries worldwide.

Continued efforts are needed to understand the critical role of materials in energy transitions and identify strategies to mitigate possible impacts from a whole supply chain perspective.

REFERENCES

———. 2017. “Mineral Commodity Summaries: Cement.” *U.S. Geological Survey, MIneral Commodity Summaries* 2017 (703): 44–45.

———. 2020. “Steel Statistical Yearbook 2020 Extended Version,” 46.

Arderne, C., C. Zorn, C. Nicolas, and E. E. Koks. 2020. “Predictive Mapping of the Global Power System Using Open Data.” *Scientific Data* 7 (1): 1–12. https://doi.org/10.1038/s41597-019-0347-4.

Carrara, S, P Alves Dias, B Plazzotta, and C Pavel. 2020. *Raw Materials Demand for Wind and Solar PV Technologies in the Transition towards a Decarbonised Energy System*. *Jrc119941*. https://doi.org/10.2760/160859.

Cormos, Calin Cristian, Konstantinos Vatopoulos, and Evangelos Tzimas. 2013. “Assessment of the Consumption of Water and Construction Materials in State-of-the-Art Fossil Fuel Power Generation Technologies Involving CO2 Capture.” *Energy* 51: 37–49. https://doi.org/10.1016/j.energy.2012.12.050.

Deetman, S., H. S. de Boer, M. Van Engelenburg, E. van der Voet, and D. P. van Vuuren. 2021. “Projected Material Requirements for the Global Electricity Infrastructure – Generation, Transmission and Storage.” *Resources, Conservation and Recycling* 164 (October 2020). https://doi.org/10.1016/j.resconrec.2020.105200.

Deetman, Sebastiaan, Sylvia Marinova, Ester van der Voet, Detlef P. van Vuuren, Oreane Edelenbosch, and Reinout Heijungs. 2020. “Modelling Global Material Stocks and Flows for Residential and Service Sector Buildings towards 2050.” *Journal of Cleaner Production* 245: 118658. https://doi.org/10.1016/j.jclepro.2019.118658.

Edelenbosch OY, Kermeli K, Crijns-Graus W, Worrell E, Bibas R, et al. 2017. Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy*. 122:701–10

Fishman, Tomer, Niko Heeren, Stefan Pauliuk, Peter Berrill, Qingshi Tu, Paul Wolfram, and Edgar G. Hertwich. 2021. “A Comprehensive Set of Global Scenarios of Housing, Mobility, and Material Efficiency for Material Cycles and Energy Systems Modeling.” *Journal of Industrial Ecology* 25 (2): 305–20. https://doi.org/10.1111/jiec.13122.

Habib, Komal, Snjólaug Tinna Hansdóttir, and Hina Habib. 2020. “Critical Metals for Electromobility: Global Demand Scenarios for Passenger Vehicles, 2015–2050.” *Resources, Conservation and Recycling* 154 (June 2019): 104603. https://doi.org/10.1016/j.resconrec.2019.104603.

He, Rui fang, Mei rui Zhong, and Jian bai Huang. 2021. “The Dynamic Effects of Renewable-Energy and Fossil-Fuel Technological Progress on Metal Consumption in the Electric Power Industry.” *Resources Policy* 71 (June): 101985. https://doi.org/10.1016/j.resourpol.2021.101985.

Holz, Christian, Lori S. Siegel, Eleanor Johnston, Andrew P. Jones, and John Sterman. 2018. “Ratcheting Ambition to Limit Warming to 1.5 °c-Trade-Offs between Emission Reductions and Carbon Dioxide Removal.” *Environmental Research Letters* 13 (6): 064028. https://doi.org/10.1088/1748-9326/aac0c1.

Kermeli K, Edelenbosch OY, Crijns-Graus W, Ruijven BJ van, Vuuren DP van, Worrell E. 2021. Improving material projections in Integrated Assessment Models: The use of a stock-based versus a flow-based approach for the iron and steel industry. *Energy*. 122434

Kermeli, Katerina, Oreane Y. Edelenbosch, Wina Crijns-Graus, Bas J. van Ruijven, Silvana Mima, Detlef P. van Vuuren, and Ernst Worrell. 2019. "The Scope for Better Industry Representation in Long-Term Energy Models: Modeling the Cement Industry." *Applied Energy* 240 (April): 964–85. https://doi.org/10.1016/j.apenergy.2019.01.252.

Marinova, Sylvia, Sebastiaan Deetman, Ester van der Voet, and Vassilis Daioglou. 2020. "Global Construction Materials Database and Stock Analysis of Residential Buildings between 1970-2050." *Journal of Cleaner Production* 247: 119146. https://doi.org/10.1016/j.jclepro.2019.119146.

Nong D, Escobar N, Britz W, Börner J. 2020. Long-term impacts of bio-based innovation in the chemical sector: A dynamic global perspective. *J Clean Prod*. 272:122738

Pihl, Erik, Duncan Kushnir, Björn Sandén, and Filip Johnsson. 2012. "Material Constraints for Concentrating Solar Thermal Power." *Energy* 44 (1): 944–54. https://doi.org/10.1016/j.energy.2012.04.057.

Rochedo PRR. 2016. Development of a global integrated energy model to evaluate the brazilian role in climate change mitigation scenarios. Tese de doutorado. COPPE/UFRJ/PROGRAMA DE PLANEJAMENTO ENERGÉTICO. *Rio de Janeiro - RJ*

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, et al. 2018. "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development." *IPCC Special Report Global Warming of 1.5 °C*, 82pp.

Ruijven BJ van, Vuuren DP van, Boskaljon W, Neelis ML, Saygin D, Patel MK. 2016. Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries. *Resour Conservation Recycl*. 112:15–36

Selliers, D de, and C Spataru. 2018. "Energy-Materials Nexus for a Low Carbon Energy System." *Presented at: 3rd AIEE Energy Symposium Current and Future Challenges on Energy Security, Milan, Italy. (2018)* , December.

Sluisveld MAE van, Boer HS de, Daioglou V, Hof AF, Vuuren DP van. 2021. A race to zero - Assessing the position of heavy industry in a global net-zero CO2 emissions context. *Energy Clim Change*. 2:100051

Stilwell, Carvalho. 2019. "Tomás Campos de Carvalho Stilwell Transition to a Low Carbon Energy System :"

USGS. 2013. "2013 Minerals Yearbook," no. December.

Vandepaer, Laurent, Karin Treyer, Chris Mutel, Christian Bauer, and Ben Amor. n.d. "LCI METHODOLOGY AND DATABASES The Integration of Long-Term Marginal Electricity Supply Mixes in the Ecoinvent Consequential Database Version 3.4 and Examination of Modeling Choices." Accessed January 20, 2020. https://doi.org/10.1007/s11367-018-1571-4.

Vidal, Olivier, Bruno Goffé, and Nicholas Arndt. 2013. "Metals for a Low-Carbon Society." *Nature Geoscience*. Nature Publishing Group. https://doi.org/10.1038/ngeo1993.

Vuuren, Detlef P. Van, Elke Stehfest, David E.H.J. Gernaat, Maarten Van Den Berg, David L. Bijl, Harmen Sytze De Boer, Vassilis Daioglou, et al. 2018. "Alternative Pathways to the 1.5 °c Target Reduce the Need for Negative Emission Technologies." *Nature Climate Change* 8 (5): 391–97. https://doi.org/10.1038/s41558-018-0119-8.

Worldsteel. 2013. "Steel Statistical Yearbook 2013." *WorldSteel Association* 1: 117.

Zhang, Shaohui, Bo Wen Yi, Ernst Worrell, Fabian Wagner, Wina Crijns-Graus, Pallav Purohit, Yoshihide Wada, and Olli Varis. 2019. "Integrated Assessment of Resource-Energy-Environment Nexus in China's Iron and Steel Industry." *Journal of Cleaner Production* 232 (September): 235–49. https://doi.org/10.1016/j.jclepro.2019.05.392.

ANNEX 1

Table 1: Material demand per GW of installed capacity used in MATE model

Technologies	Concrete (kt/GW)	Cement (kt/GW)	Al (t/GW)	Cu (t/GW)	Steel (kt/GW)	Polymers - Non-Specified (t/GW)	Polyethylene (t/GW)	Epoxy resin (t/GW)	Polyvinylchloride (t/GW)
Geothermal	-	106 [c]	11894 [c]	2218 [c]	4 [c]	-	-	-	-
Hydro	7644 [d]	982 [c]	50 [c]	69 [c]	124 [c]	-	-	-	-
Nuclear	370 [c]	58 [d]	427 [c]	60 [c]	66 [c]	-	-	-	-
Solar|CSP	1300 [g]	161 [g]	8247 [e]	2238 [f]	0,5 [e]	500 [e]	-	-	-
Solar|PV	61 [g]	9 [g]	9534 [g]	1765 [g]	68 [e]	8600 [e]	-	-	-
Wind|Offshore	400 [g]	106 [g]	1073 [g]	1823 [g]	120 [g]	4600 [e]	-	274 [c]	1750 [c]
Wind|Onshore	400 [g]	95 [g]	1585 [g]	7750 [g]	120 [g]	4600 [e]	-	450 [c]	-
Biomass|w/o CCS	150	49	500	90	92	-	1000 [c]	-	-
Biomass|w/ CCS	233	75	500	90	137	-	1000 [c]	-	-
Coal|w/o CCS	150	49 [d]	500 [a]	90 [a]	92 [a]	-	1000 [c]	-	-
Coal|w/ CCS	233 [b]	75 [d]	500 [a]	90 [a]	137 [b]	-	1000 [c]	-	-
Gas|w/o CCS	82 [a]	5 [d]	260 [a]	260 [a]	27 [a]	-	1500 [c]	-	-
Gas|w/ CCS	82 [a]	5 [d]	260 [a]	260 [a]	40 [b]	-	1500 [c]	-	-
Oil	188 [c]	29 [d]	600 [c]	1500 [c]	72 [c]	-	600 [c]	-	-

Sources: a: Vidal et al. (2013); b: Cormos et al. (2013); c:Wernet et al.(2016); d: estimated by the author; e: Carrara (2020); f: Pihl (2012); g: Stilwell (2019) (Vidal, Goffé, and Arndt 2013; Cormos, Vatopoulos, and Tzimas 2013; Carrara et al. 2020; Pihl et al. 2012; Stilwell 2019)

Preliminary results from reviewing industry modelling of low energy and materials demand, net-zero GHG futures – towards a research roadmap for novel modelling for industrial sectors in response to deep demand-side transformations.

Preliminary results of the industry modeling review, for EDITS. *18.2.2022*

Dominik Wiedenhofer[1], Jan Streeck[1], Stefan Pauliuk[2]

[1]**University of Natural Resources and Life Sciences, Vienna (BOKU)**
Department of Economics and Social Sciences
Institute of Social Ecology

[2]**Albert-Ludwigs University Freiburg**
Faculty for Environment and Natural Resources
Industrial Ecology Freiburg

Acknowledgements:
Deliverable for the EDITS Project (Energy Demand Changes Induced by Technological and Social Innovation), funded via the Research Institute of Innovative Technology for the Earth (RITE) and by the Ministry of Economy, Trade and Industry (METI), Japan. The preliminary results herein summarize the status of an ongoing collaborative reviewing effort within the EDITS consortium, with inputs from various consortium members listed below.

Keywords:
climate change mitigation; demand-side measures; energy; materials; emissions; social metabolism; modelling

EDITS
Energy Demand changes Induced by Technological and Social innovations

BOKU

SEC
Institute of Social Ecology

Abstract

Sustainable development and climate change mitigation requires a deep structural transformation of industrial production to rapidly reduce emissions, which will be more feasible if energy and materials demand are also stabilized or even reduced. This transformation will affect what is produced and how much of it is demanded, production technologies, and the structure of global and regional supply chains. A growing number of "transformative" modelling and scenario approaches are emerging, which explore low-energy and low-materials pathways by focusing on the required energy and material services instead of indiscriminate consumption, and thereby aim to model reductions in material and energy throughput. For these topics and modelling approaches, it becomes increasingly relevant to assess the energy demand changes induced by technological and social innovations. Several emerging concepts like the circular economy, the bio-economy, or the sharing economy also aim to bridge traditional silos and explicitly address the interdependencies between materials, energy, services, demand and all resulting emissions. However, existing modelling is scattered across different model families and research traditions, with varying levels of abstraction and simplifications, and are often focused on specific considerations, such as technical energy uses, specific sectors, specific products/materials/services, single countries, and so forth.

Herein, we provide preliminary results from the ongoing review of this emerging field of transformative modelling approaches addressing low energy and materials demand (LEMD) scenarios for industry models. In this reviewing effort, we aim to identify novel contributions and important next steps for further model developments. Below, we summarize the current status and report on the final design of the review process, which was developed in 2021 jointly with the EDITS consortium and approved in several plenary sessions. Ongoing research work is currently executing the research design, collecting relevant studies, conducting in-depth assessments of them, and preparing the synthesis. We here summarize some preliminary findings on conceptual considerations and about the literature that has been collected so far. The finalization of this research effort is planned until Summer 2022.

In the following, we summarize the research design and provide a conceptual foundation for the review process and LEMD modelling in general, summarizing insights from social metabolism research, industrial ecology, complex systems approaches, ecological economics and discussions around demand-side measures and societal wellbeing. We identify the following modelling traditions to be reviewed: 1) CGE-type models (neoclassical, neo-keynesian, etc), 2) econometric, partial-equilibrium, monetary stock-flow consistent modelling, 3) industrial ecology and social metabolism modelling (MFA, IOA, LCA), 4) complex systems modelling (system dynamics & ABM). We then provide preliminary results for the studies selected from these traditions and reviewed so far, and draw out some preliminary lessons and next steps, before we sketch out the key conclusions to be developed.

Section	Item (core contributions in boxes)
Point of departure	1.5-2°C goal, low demand narrative related to industry: deep transformation of energy, material, and product service demand and their impact on industry
	Role of industry in sustainable development, vision (SDG 12 and beyond) General research needs related to industry role/vision under EDITS narrative
Key aims and contributions	System definition of industry: Synthesize figs. IPCC 10.1 and Müller 2013
	Derive industry modelling principles from industry role/vision/lit. review
	Map accounting fw & model families to principles, develop model timeline
	Review best practice/cutting edge case studies on industry transformation + Map selected reserach cases to principles + Inventory of relevant case study aspects: resolution, disruption, ...
	Synthesize and discuss + Model development needs in relations to reserach questions asked + Map out an interdisciplinary industry model landscape + Links to other sectors + Refine industry modelling vision in light of EDITS and 1.5°C narrative

Timeline & planned finalization:

- Review and assessment of specific models ongoing, to be finalized until April 2022
- Synthesis of research frontiers and identification of research roadmap: April-July 2022
- Submission to Annual Review of Resources & Environment in August 2022

Table 1: Alphabetical list of EDITS researchers involved in the ongoing reviewing process.

Akimoto	Keigo	Research Institute of Innovative Technology for the Earth
Boza-Kiss	Benigna	International Institute for Applied Systems Analysis
Cullen	Jonathan	University of Cambridge and Fitzwilliam College, Studies for Engineering
Edelenbosch	Oreane	International Research University - Universiteit Utrecht
Godoy Leon	Maria-Fernanda	University of Ghent
Grubler	Arnulf	International Institute for Applied Systems Analysis
Ju	Yiyi	University of Tokyo
Jupesta	Joni	Research Institute of Innovative Technology for the Earth
Kim	Yong-Gun	Korea Environment Institute
Krey	Volker	International Institute for Applied Systems Analysis
Magalar	Leticia	CENERGIA - Centre for Energy and Environmental Economics, Energy Planning Program, COPPE, UFRJ
Masanet	Eric	McCormick School of Engineering and Applied Science, Northwestern University
Niamir	Leila	Mercator Research Institute on Global Commons And Climate Change
Pauliuk	Stefan	University of Freiburg
Roy	Joyashree	Asian Institute of Technology (AIT) / The Breakthrough Institute
Streeck	Jan	Universität für Bodenkultur (BOKU), Institut für Soziale Ökologie (SEC)
Sugiyama	Masahiro	University of Tokyo
Tavoni	Massimo	Politecnico di Milano School of Managmenet
van Ruijven	Bas	International Institute for Applied Systems Analysis
Verdolini	Elena	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (EIEE/CMCC)
Wiedenhofer	Dominik	Universität für Bodenkultur (BOKU), Institut für Soziale Ökologie (SEC)
Wilson	Charlie	University of East Anglia, Tyndall Centre for Climate Change Research
Worrell	Ernst	University of Utrecht

Contents 1

Abstract 2

1. INTRODUCTION 5

2. REVIEW SCOPE, PROCESS AND METHODS FOR KNOWLEDGE SYNTHESIS 9

3. WHY IS DIRECTLY ADDRESSING ENERGY AND MATERIAL SERVICES CRITICAL FOR REVIEWING AND DEVELOPING TRANSFORMATIVE LEMD INDUSTRY MODELLING APPROACHES? 12

4. CONCEPTUALIZING THE SCOPE OF "INDUSTRY" AND DERIVING CRITICAL CONSIDERATIONS FOR LEMD INDUSTRY MODELLING 15

5. PRELIMINARY FINDINGS OF THE ONGOING LITERATURE REVIEW 19

6. DISCUSSION OF PRELIMINARY FINDINGS AND NEXT STEPS 21

7. MODEL DEVELOPMENT OPPORTUNITIES AND NEEDS: TOWARDS A RESEARCH ROADMAP 22

REFERENCES 23

Table 1: Alphabetical list of EDITS researchers involved in the ongoing reviewing process. 3
Table 2: Research questions for this literature review 9
Table 3: Criteria for inclusion/exclusion of models and scenarios for this review 10
Table 4: Identification and grouping of modelling & knowledge traditions to be reviewed 11
Table 5: Prominent journal outlets of the 81 screened studies. For the full list of all studies collected so far, see Table 6 at the end of this deliverable. 20
Table 6: Bibliographic information on the literature identified and assessed so far. 25

Figure 1: The Energy Service Cascade linking the environment, resources, industry, material and energy services, to societal wellbeing (Kalt et al., 2019) 13

Figure 2: Towards a biophysically consistent systems definition for industry modelling and its interlinkage with energy supply and final demand. Top rows: existing concepts, bottom row: first draft of concepts for this industry modelling review. 17

Figure 3: Preliminary analysis how and if 65 studies assessed in more detail fulfill the four criteria of relevance. For the full list of all studies collected so far, see Table 6 at the end of this deliverable.... 19

Figure 4: Preliminary bibliometric analysis of methods used in 81 screened studies (several methods might have been applied per study). For the full list of all studies collected so far, see Table 6 at the end of this deliverable. 20

1. Introduction

Tackling the unfolding multiple socio-ecological crises such as climate change, biodiversity loss and persistent poverty requires at the same time a reduction and a transformation of global resource use and emissions (IPBES, 2019; IPCC, 2018; UNEP-IRP, 2019). However, despite ever more visible environmental impacts, society is currently heading in the opposite direction: around the turn of the millennium, as economic development in China and other emerging economies spurred, global resource use of metals, non-metallic materials and biomass, as well as fossil energy carriers and all resulting emissions accelerated. In 2015, global resource use reached 89 Gt/year of extraction (1 Gt = 1 billion metric tons), resulting in 46 Gt/year greenhouse-gas (GHG) emissions (Krausmann et al., 2018). While the COVID-19 crisis substantially affected global production and consumption, global energy use and emissions are quickly rebounding. Crucially, extraction and processing materials by industry directly and indirectly causes 25 - 35% of global GHG emissions and has thereby become the most important source of emissions (Lamb et al. 2021; Hertwich 2021).

Climate change mitigation strategies are predominately based on efficiency improvements of supply-side technologies and decarbonizing energy supply, as well as risky end-of-pipe solutions such as carbon capture and storage and other 'negative emissions' technologies (Anderson & Peters, 2016; Creutzig et al., 2018; Stechow et al., 2016). The majority of climate change mitigation scenarios also assumes a strong continuation of economic growth, thereby only exploring some of the relevant socio-economic option space (Keyßer and Lenzen, 2021). Alternatives include low-growth, steady-state, no-growth or degrowth pathways (Jackson and Victor, 2019; Keyßer and Lenzen, 2021; Victor, 2012; Victor and Rosenbluth, 2007). It is increasingly clear, that reducing environmental impacts and limiting climate change to 1.5-2°C only through technological solutions and production efficiency, without addressing demand and (over)consumption, is going to be risky or even unattainable in the required time frame.

This has led to the increasing recognition that demand-side measures for reducing resource use and emissions are required (Creutzig et al., 2016; Creutzig et al., 2018; Creutzig et al., 2020; Creutzig et al., 2021). Creutzig et al. (2021) define demand-side measures (options) as '*mitigation opportunities that involve individuals or industrial end users of products, services or processes.*' Such demand-side measures would substantially increase the feasibility and reduce costs for climate change mitigation measures (Grubler et al., 2018). While at high demand for materials and energy, climate change mitigation will be expensive and needs to happen early and rigorously, lower material and energy demand allows for leeway in temporal execution, stringency of measures and budget.

Modelling demand-side measures for mitigating resource use and emissions are however so far quite limited and fragmented across approaches and traditions, despite their strengths: lowering the independence from risky technology options and synergistic effects of mitigating environmental impacts while at the same time increasing well-being (Creutzig et al., 2018; Creutzig et al., 2021). The underrepresentation of demand-side research might on the on hand be due to the heterogeneity and multitude of consumption patterns and demand types, or end-uses (food, shelter, mobility, communication, etc.; Creutzig et al., 2020). On the other hand, the assessment of demand-side measures spans the global system of production and consumption for which a non-holistic perspective can easily miss shifts of environmental impacts between industrial and end-use sectors within countries but also across international supply chains. The investigation of technological and social demand-side innovations and their repercussions through (global) industry thus requires a system-wide research perspective considering heterogeneity, path dependencies due to accumulated material stocks and global supply chains. Clearly, assessing strategies and measures for demand-side solutions requires novel modelling approaches and further developing existing models (Creutzig et al., 2021, 2018; Keyßer and Lenzen, 2021).

Through this review of current work, we aim to inform future advances in industry modelling of demand-side measures by focusing on three critical aspects:

- Firstly, "upstream" industry activity directly and indirectly delivers goods and services demanded; resulting in energy and materials savings of demand-side measures to materialize across global supply chains and through savings in national energy supplies and raw materials extraction by extractive industries. To capture system-wide effects of demand-side changes and innovations in service provision, global supply chains and sector interactions need to be modeled systematically, in order to detect potential rebound effects and burden shifting between different sectors of the economy (e.g. electric vehicles reducing GHG emissions in final end-use but increasing emissions for vehicle manufacture in the industry sector; Brockway et al., 2021; Pauliuk et al., 2017; Plank et al., 2018).
- Secondly, novel approaches to modelling and conceptualizing the biophysical and industrial basis of sufficient high-quality service provision and its contributions to human wellbeing are required. Materials and energy flows and the material product stocks are only the physical means to provide functions and services, which in turn contribute to social wellbeing in a context-specific manner (Haberl et al., 2017; Haberl et al., 2019; Kalt et al., 2019). What constitutes a desirable and sufficient level of „low demand" is therefore an open question to be addressed, which is needed to inform innovations in and scenarios for industry and energy system modelling. This includes systematically linking the necessary material and energy flows to the respective material product stocks, which jointly play a crucial role in service provision (Grubler et al., 2018; Haberl et al., 2017; Millward-Hopkins et al., 2020; Pauliuk et al., 2020; Pauliuk & Müller, 2014; Rao et al., 2019).

Drawing on the notion of the stock-flow-service nexus (Carmona et al., 2017; Haberl et al., 2017; Haberl et al., 2019; Kalt et al., 2019), which describes the interplay of resource flows, material accumulations in long-lived product stocks such as buildings, infrastructure and machinery ('material stocks'), and the services that their interplay provides for society, material stocks play a particularly important role in coupling resource use, emissions and service provision (Pauliuk and Müller, 2014). The efficiency of alternative service provision models via different stock-flow relations is thus at the center of mitigating resource and energy demand as well as climate change from a socio-metabolic perspective on demand-side solutions.

- Thirdly, thermodynamic and mass-balanced consistency across sectors, industries, energy supply, final demand and the underlying physical stock-flow relations is crucial (Haberl et al., 2019; Pauliuk et al., 2017; Pauliuk and Hertwich, 2015). It is necessary to adress the connectedness of materials, energy and GHG emissions, so that synergies but also burden shifting between different materials, energy and emissions, as well as intermediate and final demand can be modelled properly. For example, transitioning towards a renewables-based energy system requires more materials, some of them critical and some energy- and emissions intensive (Kalt et al., 2021). Changing infrastructure and transforming cities and settlements to enable car-free mobility and have sufficient high quality living space will also drive material use, which in turn requires energy and causes emissions. Being able to comprehensively model these interactions between materials, energy and demand-side measures is therefore critical for informing climate change mitigation strategies.

These considerations inform the design of this review of existing industry modelling approaches. We aim to address the following overarching research questions:

- *Which biophysical and socio-economic aspects of society should industry and supply chain modelling cover, to become able to model the transformative structural changes implied in low-energy & materials demand (LEMD) scenarios?*
- *How do current models cover the relations between materials-energy-emissions, and the actual services and contributions to wellbeing required for a sustainable LEMD future with high wellbeing?*

Previous reviews touched on some of these aspects and these are utilized to synthesize key needs and conceptualizations in this review. A sufficiently high materials and industry resolution, as well as thermodynamic consistency are identified as critical limitation in current IAMs (Pauliuk et al., 2017). Improving industrial process & technology representation and process models in large comprehensive models is similarly seen as crucial (Bataille et al. 2021). Modelling novel strategies, like the circular economy, the sharing economy, or sufficiency, require thermodynamically complete representations of material cycles and feedbacks to energy supply (Aguilar-Hernandez et al., 2021; McCarthy et al., 2018). Depictions of stock-flow-service nexus relations and specific indicators on functions and services enables moving beyond aggregate consumption as “demand” representation (Haberl et al., 2017; Kalt et al., 2019; Rao and Min, 2017). Macro-economic modelling of demand-side measures and sustainability transformations requires addressing employment, incomes, inequality and financial stability (Hardt and O’Neill, 2017).

Herein, we focus on a broad range of different modelling traditions, aiming to assess how they deal with the dependency between materials, energy and emissions and reviewing, insofar they are useful for low demand modelling. In this report on preliminary findings from the industry review working group, we summarize the current status of ongoing research work. We herein document the final design of the review process, which was developed in 2021 jointly with the EDITS consortium and approved in several plenary sessions. Ongoing research work is currently executing the research design and we here summarize preliminary findings on conceptual considerations, as well as on the literature that has been collected so far. Finalization of reviewing work and submission of a manuscript to a peer-reviewed scientific journal is planned for Summer 2022.

In section 2 we present the final review scope, design and process developed in the working group and with the EDITS consortium. In section 3 we provide conceptual clarifications on material and energy services and underlying stock-flow relations. In section 4 we develop a interdisciplinary systems definition of industry modelling and its relation to energy supply and final demand. We then summarize key principles to be ideally addressed in novel and transformative modelling approaches, which was developed within the working group and with the EDITS consortium. In section 5 we summarize the literature which has been collected, screened and partially assessed so far. In section 6 we sketch preliminary insights and discussion points emerging from the reviewing work so far. In section 7 we list the key issues to be addressed over the next months to develop overall conclusions and a research roadmap for future model development.

2. Review scope, process and methods for knowledge synthesis

The scope of this research is about industry modelling tackling materials-energy-emissions relations for low demand scenarios across different research traditions. This broad scope necessitates a broad set of different disciplinary expertise to be recruited for this review. The working group successfully recruited from the EDITS consortium and from some selected external collaborators (Table 1).

The review focuses on general principles and specific models and scenarios which investigate low-energy and low-materials demand (LEMD) futures, which deliver high-quality and sufficient goods and services to contribute to improving wellbeing for all. For this scope and review, we employ two research strategies: firstly, we develop comprehensive and interdisciplinary systems definitions and conceptualizations of energy and material services, industry modelling and key principles for LEMD, and identify modelling families or research traditions/approaches to be reviewed further. Secondly, from the large group of collaborators, we formed sub-teams to dive into 'their' respective modelling families and research traditions, to selectively identify and review recent innovative models and scenarios. This enables a broad assessment and synthesis of current progress at the respective research frontiers. The review aims to answer the following research questions (Table 4).

Table 2: Research questions for this literature review

Overarching research questions	
a)	Which biophysical and socio-economic aspects of society should industry and supply chain modelling cover, to become able to model the transformative structural changes implied in low-energy & materials demand (LEMD) scenarios?
b)	How do current models cover the relations between materials-energy-emissions, and the actual services and contributions to wellbeing required for a sustainable LEMD future with high wellbeing?
Specific research questions aimed at the modelling literature	
c)	Which existing models/case studies deliver on criteria 1-4 and how (see below)?How are demand for functions and material & energy services defined and operationalized, relating to the different stages of the energy service cascade (Kalt et al., 2019)?
d)	How is the relation of demand to industry modelled?
Synthesis research questions	
e)	How do the different modelling traditions handle criteria 1-4 to model LEMD futures?
f)	What are next steps and recommendations for existing and new innovative modelling approaches exploring LEMD futures?

The research and review process is structured into five main phases/steps, each with their own rationale and approach. Firstly, we summarize conceptual framings on material and energy services utilizing previous work of some of the authors (see below, (Kalt, Wiedenhofer, et al. 2019), and establish conceptual clarifications for industry system definitions and synthesize a number of key conceptual issues for low-energy & low-materials demand net-zero GHG industry modelling. These sections are based on literature synthesis and expert judgement.

Secondly, we identify current innovative models and scenarios at the research frontier, through a selective expert-driven literature search and reviewing process (this step is currently ongoing). For this purpose, scientific literature databases are screened, citation snowballing is conducted and expert-driven selections are conducted, to identify models and literature satisfying a set of four criteria of relevance (see below). These four criteria are derived from the motivation of this study articulated in the introduction and further elaborated upon in the conceptual sections below (Table 2). We decided to interpret these criteria quite broadly and also include studies only partially complying with them, to cover a broad range of innovative approaches which either already tackle the overall question, or are deemed useful and highly relevant for further developing novel modelling frameworks and methods.

Table 3: Criteria for inclusion/exclusion of models and scenarios for this review

1)	Does the study model materials, energy and GHGs with an empirical basis in physical units?
2)	Does the study use social and/or physical indicators on demand, services, wellbeing & social progress, i.e., non-monetary indicators for material and energy services?
3)	Does the study cover industry as intermediate user/supplier and does it contain modelling of industrial production, e.g. intermediate (upstream/downstream) inputs and/or outputs from industry for a certain service/final demand?
4)	Does the study model demand-side changes for industry output, e.g. is demand seen as variable and/or is used as scenario variable (instead of being a non-questionable given): E.g., explorations of low-demand, low-growth, stabilization, degrowth, reductions of demand/services/consumption?

Fourthly, literature satisfying these four criteria of relevance are screened, assessed in-depth and discussed among the authors, following a consistent review framework which had to be established through an iterative and interdisciplinary process from Spring 2021-Winter 2021. This work is currently ongoing. The following information is gathered for each model/literature, the full assessment list will be made available as supplementary information to the final paper. For a short overview on the already selected literature, see Table 6 at the very end of this report.

A) short statement how criteria 1-4 are met,
B) scope of study (geographical, temporal),
C) resolution of modelling (sectors, materials, products/services, energy carriers, GHGs, other elementary flows),
D) highlights of the paper, highlights for LEMD modelling, summary quotes,
E) framework, method, data, results, remarks,

F) bibliometric information. This collection of information is then used to concisely review current state-of-the-art innovative modelling efforts.

From the group of authors and the EDITS consortium, the following four knowledge and modelling traditions were identified as relevant for this reviewing process (Table 3).

Table 4: Identification and grouping of modelling & knowledge traditions to be reviewed

1)	CGE-type modelling: Classical IO macro-economic analysis (socio-economic early work by Leontief and others), Computable General Equilibrium Models (CGEs), New-Keynesian models, IAMs
2)	Empirical/Econometric/partial-equiblirum/stock-flow consistent modelling: Monetary stock-flow consistent macro-economic modelling, partial equilibrium models, econometric models, Other models in macro-economics tradition
3)	Biophysical industrial ecology/ecological economics modelling: LCA: attributional vs consequential; MFA: accounting and dynamic MFA; Modern EE-IO analysis, e.g. footprinting, waste-IO & supply chain analysis
4)	Complex systems modelling: Agent Based Models, System Dynamics, Analytical models

Finally, based on this effort and judgement of the involved authors, synthesis statements for each modelling tradition were developed, sketching out the current research frontier, further research needs and potential synergies and complementarities between modelling traditions.

3. Why is directly addressing energy and material services critical for reviewing and developing transformative LEMD industry modelling approaches?

For LEMD modelling and EDITS, the notion of energy and material services is critical. The use of the concept is usually motivated by the recognition that it is generally not energy or energy carriers, or money and materials themselves, which are demanded by people, but rather it is services delivered by materials and energy that provide benefits for society and human well-being (Carmona et al., 2017; Fell, 2017; Grubler et al., 2018; Haberl et al., 2017; Kalt et al., 2019). Common examples are: heating fuels vs. conditioned living space; electricity vs. illumination; transport fuels vs. mobility. This example already illustrates, there is also material services involved, which emerge from the product 'stocks' of the building or the technical appliances making up the heating system. Critically, industry as well as energy supply are then intermediate 'upstream' suppliers enabling energy and material services, as they transform raw materials into products and energy carriers to be utilized to provide functions and services.

We here synthesize and expand upon recent work by some of the authors, drawing on the Energy Service Cascade to conceptualize how industry relates to the materials and energy services required for their contributions to wellbeing (Figure 1) (Haberl et al., 2019, 2017; Kalt et al., 2019). The first element in this cascade is 'biophysical and societal structures'. We explicitly discern natural structures, i.e. naturally occurring material and energy resources, from socio-technical structures, including manufactured capital and labor required to make energy and products available to end-users and convert it to useful energy. 'Structures' in the ESC include the entire material and energy conversion chain: primary energy conversion to secondary and final energy and ultimately useful energy (or exergy). Apart from structures performing energy conversion, we argue that 'structures' also comprises artefacts which are often disregarded in the context of the energy conversion chain, such as building envelopes in the case of space heating or road and rail infrastructures and their spatial structures in case of freight and personal transport. Cullen and Allwood [21] introduced the term 'passive system' for these non-energy converting technical components, which are supplied by industry.

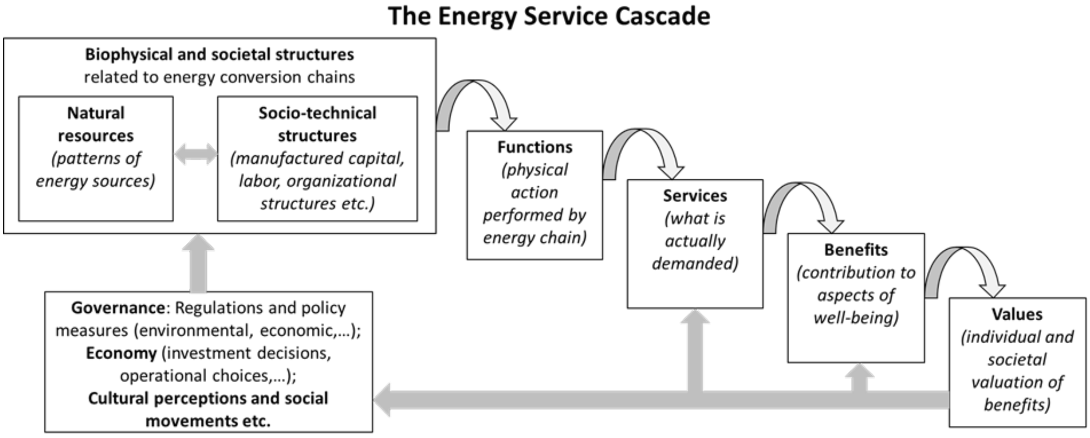


Figure 1: The Energy Service Cascade linking the environment, resources, industry, material and energy services, to societal wellbeing (Kalt et al., 2019)

The second element in the cascade is 'functions'. A function is a physical action performed by an energy conversion chain, for example accelerating a vehicle, transmitting thermal energy to living space or emitting photons for illumination. Hence, functions are measurable in physical units but not necessarily energy units. Functions are understood in the ESC as follows: Humans find it useful that a vehicle is accelerated by a vehicle's internal combustion engine, or that food is kept fresh in a fridge. But – and this is the crucial difference to services –these useful capacities are not per se generators of well-being and merely help to provide a service, like enabling a person to reach a workplace or consuming fresh and heathy food.

Services represent the third step in the cascade and are usually conceptualized as 'what humans actually demand'. Services enhance well-being but are not identical to well-being contributions. To help differentiate them from functions, we proposed the following definition: While functions are conceptualized as being independent from actual beneficiaries, 'a service is only a service if a human beneficiary can be identified' (Potschin-Young et al., 2018, p. 578). For example, no service is attributable to illuminating and heating vacant buildings, although the functions are in place.

Clearly, services are a stakeholder driven concept, where culturally specific perceptions play an important role. Therefore, it must be critically scrutinized what the actual demands of certain societal groups are, how they are articulated and who gets to participate in defining the actual 'service'. Requested service levels are to some degree defined by subjective benefits they provide and influenced by historical and cultural backgrounds. Just like in the case of ecosystem services, energy services generate 'benefits': actual contributions to human well-being such as health and life satisfaction, which are associated with human needs, as defined for example by (Max-Neef, 1991) (e.g. subsistence, protection, idleness etc.). Benefits are the outcome of services: Not having to freeze in winter (i.e. thermal comfort; an energy service) contributes to bodily health (a benefit and contribution to well-being). Similarly, illuminated living space (a service[1]) enables the inhabitants to be active after sunset; to enjoy various forms of entertainment or participate in social life (benefits). The relationship between energy services and human needs is often emphasized in connection with energy poverty, but it is central to all energy use (Brand-Correa et al., 2018; Brand-Correa and Steinberger, 2017).

Strong concerns have been voiced if such benefits are linked to a narrow utilitarian approach reducing benefits to economically measurable preferences in monetary units (e.g. as willingness to pay), or whether a broader scope must be applied that also takes cultural perceptions, moral concerns and human freedom into account (Jax et al., 2013; Lamb and Steinberger, 2017). Individual attitudes and preferences play a major role for services demanded and benefits derived from them: Driving a car might be considered to be fun (service: entertainment) and as a major contribution to life satisfaction (benefit) by some, while many others might consider it an inevitable part of a daily routine to earn a living (service: mobility; benefit: subsistence). These concerns directly apply to the energy and climate change mitigation discourse about demand-side measures and overcoming lock-in effects (Creutzig et al., 2021, 2018; Seto et al., 2016). Thus, the actual benefits from material and energy services can be seen quite differently and in conflicting ways.

The final component of the ESC is therefore 'values' and refers to individual attitudes, preferences and habits as well as societal norms and their manifestations. We differentiate into economic and non-economic values, which can translate into willingness to pay for energy services. Moreover, benefits influence individual preferences and trigger behavioral patterns that are not economically motivated. Two examples: 1) A person living in an urban region and appreciating the benefits of good access to public transport will likely have other convictions regarding an ideal place to live or questions related to traffic policy than a rural dweller used to moving by car. 2) People with an IT savvy social circle and frequently engaged in communication via the internet might be more inclined to support public spending in data infrastructures than people with traditional, local jobs and mostly regional social connections.

Conversely, habits and societal preferences ('values') also influence the demand for an energy service as well as the perceived benefits from it. These mechanisms are represented by the feedback arrow from 'values' to 'services' and 'benefits'. And finally, 'values' exert influence on the evolution of biophysical structures through numerous, diverse and complex mechanisms involving governance, economy, culturally motivated claims articulated by e.g. social movements etc.

[1] The difference between the function 'emitting photons for illumination' and the service 'illuminated living space' may seem subtle, but if nevertheless relevant if we consider that requirements on illumination depend on spatial and architectural settings.

Finally, and directly relevant for thinking about industry modelling and LEMD futures, the ESC shows how natural resources are mobilized to deliver material and energy services and its conceptualization indicates the multiple feedbacks and interdependencies to be expected between a LEMD future with high wellbeing and a net-zero GHG industry supplying the required materials and energy. For the ESC socio-technical structures are critical, as the majority of the ESC is part of the socio-economic system. The entire ESC relies on industrial systems and technologies along the entire materials and energy conversion chains, as well as multiple 'passive systems' of infrastructure, buildings and manufactured capital in general. These passive systems and upstream industrial processes themselves also require maintenance and intermediate inputs, therefore inducing energy and material flows.

4. Conceptualizing the scope of "industry" and deriving critical considerations for LEMD industry modelling

Different modelling approaches rooted in distinct theoretical paradigms have developed their own conceptualizations of what industry is and how it is exactly delineated. Based on the ongoing reviewing process, the scope and aims of EDITS and the expert inputs from the EDITS consortium, a number of critical considerations for better industry modelling of LEMD futures were identified, which also informed the development of the systems definition in Figure 2. For the purpose of this review of modelling industry for LEMD futures, we developed the following conceptual clarifications.

We delineate and define "industry" by merging conceptualizations from IPCC AR5, SNA/SEEA, economy-wide material flow accounting, socio-metabolic research and industrial ecology (Eurostat, 2012; Fischer-Kowalski et al., 2011; Krausmann et al., 2017; OECD, 2008; Pauliuk and Hertwich, 2015). This definition includes extractive industries, materials processing industries, manufacturing and construction industries, as well as waste management and recycling industries (Figure 1). This definition excludes the internal dynamics of buildings, mobility and energy supply, however it includes their multiple interactions with industry, which needs to addressed in a proper industry modelling (i.e. industry supplying materials and products for buildings, energy supply for industry, transport requirements driven by industry activity, etc) (Figure 1).

From an industrial ecology and socio-metabolic perspective, we furthermore conceptualize industry as consisting of multi-layered and interdependent material cycles, ranging from raw materials extraction, through processing and intermediate uses, to delivering for final demand (Figure 1). These material cycles are powered by energy flows and are transformed in and by physical capital stocks, as well as labour. We conceptualize these flows and stocks as socially organized in globally integrated supply chains and production-consumption networks.

From an ecological economics and complex-systems perspective we see industry as an intermediate user and supplier to final demand, through a network of (globally) interlinked sectors. Industry utilizes physical capital stocks and energy flows in the process of transforming materials into goods and services via joint production of wanted and unwanted outputs, as well by using labor and monetary capital (Figure 1). Industry delivers goods and services to households, governments and as investment, also always producing unwanted (unintended) by-products and waste (most basically, due to laws of thermodynamics).

From a socio-ecological perspective, we see actors in industry as having very different roles, ranging from producers and (intermediate) consumers of materials, energy, waste and emissions, to owners of capital assets, decision-makers on investments and business models, employers, and regionally to globally influential socio-political actors.

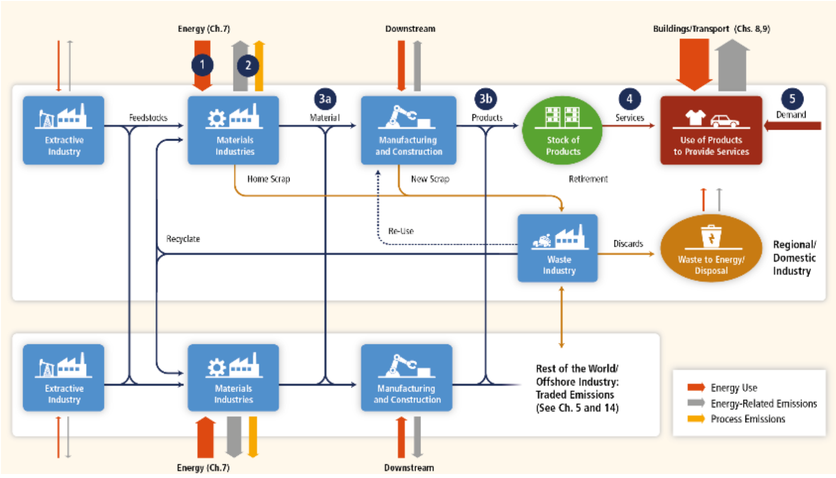
Industrial processes are widely differentiated regarding technology and provenance of goods across the globe. Modelling the phasing in of low demand options requires a detailed (technology-rich) depiction of different technologies in the context of an industrial network. We depict differentiated global supply chains with increasing degree of manufacturing, energy supply, and the need to treat waste and the opportunity to recover and recycle materials *Industry is grouped into primary (resource extraction), secondary (material production, energy supply, waste mgt., and manufacturing) and tertiary sectors (service providers). These process groups are responsible for certain environmental impacts and have specific locations, and further process and regional disaggregation is possible, depending on specific research questions and data availability.*

Industrial processing is required to convert natural resources into useful products and to recover valuable materials from waste. Its output is linked to and satisfies societal demand: *Industry is an intermediate sector, located in between the natural resources, final consumption, and final sinks.*

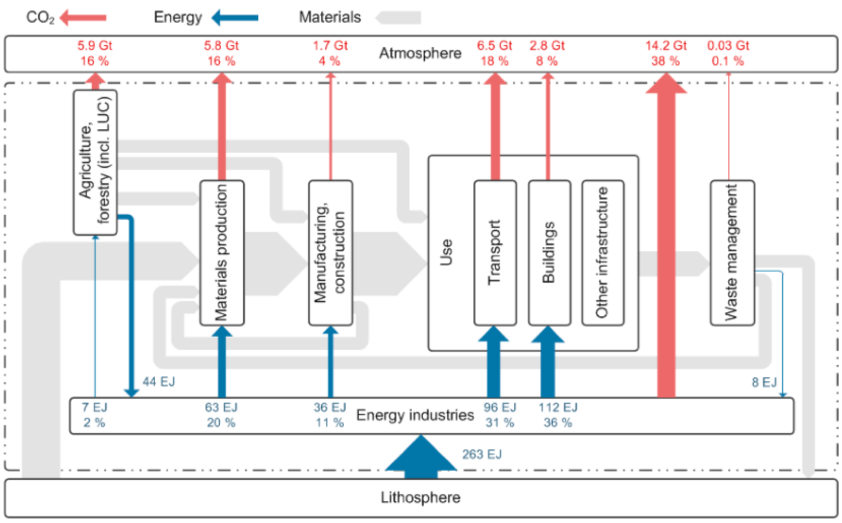
Industrial commodities are traded and on average, there is a supply-demand equilibrium: *Industry output is exchanged on markets (bipartite system structure, not shown in figure above).*

Industrial processes require fixed assets for their functioning (factories, machines, tools, etc.), and these assets represent large capital investments and material stocks. A low demand transformation of industry requires capital modification and replacement, new skills, and often additional material resources: *The different functions of industrial assets (capacity, capital, material stocks) are explicitly represented at the required level of detail to allow for considering capital constrains to the transition.*

a) Systems conceptualization from IPCC (Fischedick et al., 2014)



b) Systems conceptualization in socio-metabolic and industrial ecology research (Müller et al., 2013)



c) Preliminary proposal for a systems definition merging biophysical, socio-metabolic and socio-economic consistency considerations.

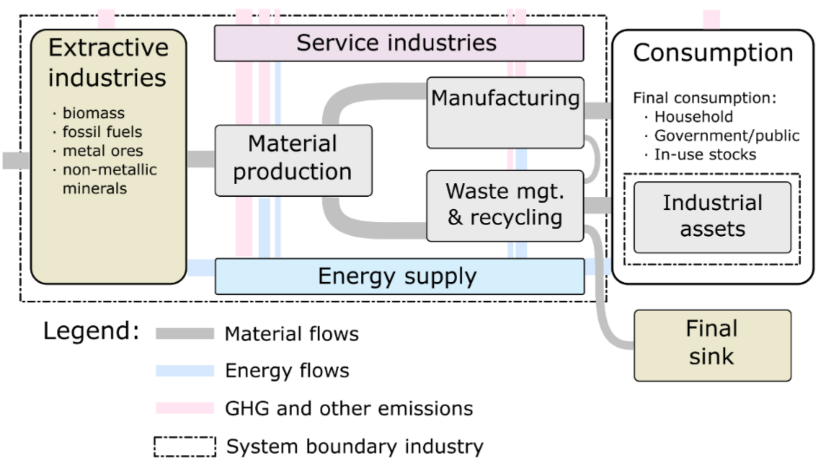


Figure 2: Towards a biophysically consistent systems definition for industry modelling and its interlinkage with energy supply and final demand. Top rows: existing concepts, bottom row: first draft of concepts for this industry modelling review.

Industrial processes are linked to resource use, emissions, environmental impacts, labor and skill demand: *A detailed and multi-layer (economic, physical, social) assessment of industrial process is needed to depict possible transition pathways.*

Resource and impact trade-offs often materialize in industry: E.g., more copper and Al required in the future, but less cadmium. Recycling opportunities depend on the development of material consumption and in-use stocks over time: *Detailed representation of material cycles, including in-use stocks and their age structure, is needed.*

Biophysical and thermodynamic consistency is crucial for LEMD modelling, which covers mass-balance, stock-flow consistency, energy conservation, entropy creation, and matching sources and sinks. Industry output needs to be supply-demand consistent, material output needs to be consistent with final demand for products, etc.

Need to consider rapid phase-out and premature capital retirement (stranded assets) for substantial transformation and response to LED futures on the demand side.

Industry has a biophysical basis in material and energy stock-flow relations, and it has a monetary layer consisting of prices, costs, sales and profits. Both monetary and physical “layers” have their own rules of consistency (e.g. thermodynamics vs accounting & book-keeping rules), which need to be considered explicitly.

For realistic and feasible scenarios: detailed policy modelling (subsidies, regulations, phase-out, eco-design, etc.), economic (business model assessment), and behavioral options (adaptation of new businesses or lobbying against change) is needed.

Final demand by households and its contribution to wellbeing consists of materials and energy services required to perform certain functions and activities, ranging from housing, adequate nutrition, social signaling, etc. These considerations are not properly covered in costs and prices (monetary valuation). *It therefore becomes necessary to model demand also in non-monetary units, e.g. physical and/or social indicators.*

Ideally, LEMD industry modelling can address non-linear changes, as well as disruptive & structural transformations, versus only showing marginal changes and adjustments

Ideally, LEMD industry modelling covers also socio-ecological feedbacks and biophysical limits (e.g. damage functions, limits, constraints, boundaries).

5. Preliminary findings of the ongoing literature review

We here summarize the current literature base identified in the reviewing process and discuss some preliminary findings. We generally aim to identify and comparatively review current innovative models and cutting-edge case studies from each modelling family (see section above), which provides insights into the transformation of industry, complying with stringent climate and sustainability targets.

So far, we collected 81 studies with potentially innovative modelling content. For the full list of all studies collected so far, see Table 6 at the end of this deliverable. 65 studies underwent initial assessment, which gives an overview in how far the four selection criteria are met (Figure 2a): roughly 80% of studies cover criteria 1 & 4 in that they include the modelling of at least two physical entities from materials, energy and GHGs (criterion 1) and industry as an intermediate user and supplier to provision of services to final demand. In contrast, only 2/5th of assessed studies include variations of demand or even low demand scenarios, and only 1/3rd of studies includes physical or social indicators of demand, services or well-being (e.g. person-kilometers travelled, or Social Progress Index). These studies were however still considered interesting due to their modelling strategies. Coverage of all four criteria was confirmed for only 11 studies so far.

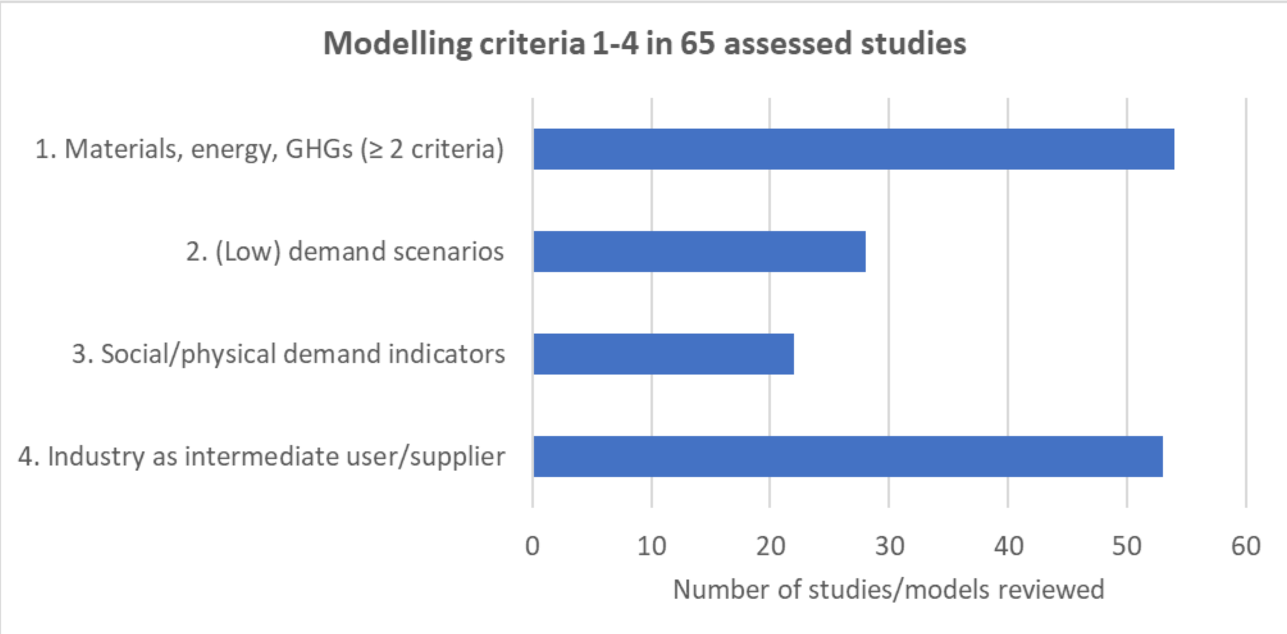


Figure 3: Preliminary analysis how and if 65 studies assessed in more detail fulfill the four criteria of relevance. For the full list of all studies collected so far, see Table 6 at the end of this deliverable.

Regarding modelling traditions and methodology, Figure 2b shows the count of applied methods within the total sample of 81 studies. Material Flow Analysis based approaches (23) and Integrated Assessment & Sectoral models (17) are most frequently applied, followed with a certain gap by macro-economic models (9), and all other distinct approaches comprising between 5-6 applications. Also, method combinations of Integrated Assessment Models with Material Flow Analysis (4 counts) and combinations of econometric models with LCA/MFA (2 counts) were present (not shown in Figure 2).

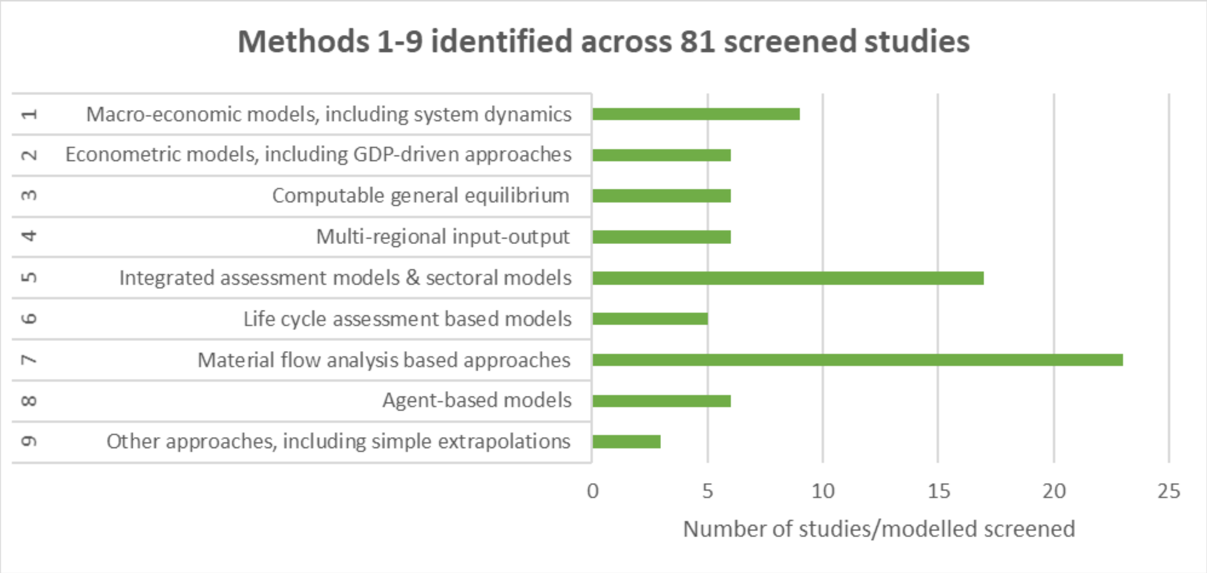


Figure 4: Preliminary bibliometric analysis of methods used in 81 screened studies (several methods might have been applied per study). For the full list of all studies collected so far, see Table 6 at the end of this deliverable.

Prominent publications outlets of the studies in our sample of literature are spear-headed by the journals Applied Energy, Environmental Science & Technology, Global Environmental Change and Energy (Table 5).

Table 5: Prominent journal outlets of the 81 screened studies. For the full list of all studies collected so far, see Table 6 at the end of this deliverable.

Journals	Number papers in sample
Applied Energy	12
Environmental Science & Technology	8
Global Environmental Change	7
Energy	7
Ecological Economics	6
Energy Policy	6
Nature Communications	5
Journal of Industrial Ecology	3
Resources, Conservation and Recycling	3

6. Discussion of preliminary findings and next steps

Several preliminary insights emerge from collecting, screening and assessing industry modelling studies.

- Only very few models include non-monetary indicators of physical demand/functions/services, and their contributions to well-being. This however has been identified as indispensable for connecting demand-side measures with transformative industry modelling in a physically meaningful way.
- Very few models fully link materials-energy-emissions in a thermodynamically consistent manner. Those who do, often are rather coarse in their representation of socio-economic interdependencies and dynamics driving changes.
- Models with comparatively better representation of socio-economic complexity and dynamics usually do not comply with thermodynamic principles.
- The reviewed models seem to be either too aggregate, or too detailed, in light of modelling requirements and key principles identified above. When considering the multiple properties which are important for modeling industry transformation (detailed physical and economic representation of industrial assets and production flows, detailed representation of the political and legal framework and form behavior given these circumstances, etc.) comprehensiveness at sufficient detail is a criterion hardly achieved.
- An important next step is to broaden the search strategy to find relevant models and potentially invite external collaborators for additional expertise, especially regarding complexity modelling, as well as heterodox/ecological macro-economic modelling.
- The key next step is to conduct a second round of in-depth reviewing of those studies deemed to be relevant, to extract additional and more specific insights into model principles, methods, and implementations.
- A question for further exploration is, how the required model comprehensiveness and detail can be achieved in a resource-efficient way, targeted to the ultimate goal of models to inform real life decisions.

We will conclude the detailed assessment of studies within the next months, which afterwards allows for mapping the current modelling practices to the criteria identified as indespensible for modelling of industry transformations.

7. Model development opportunities and needs: towards a research roadmap

This discussion section aims to evaluate which modelling techniques are useful for LEMD futures and which are not, based on the criteria and modelling needs identified above. We also aim to provide an assessment of which modelling approaches should be used for LEMD modelling and which further developments seem pertinent. Topics to be addressed in the discussion of model development needs and opportunities are:

- What are the key gaps in the reviewed modelling approaches and specific models/scenarios in terms of geographical & biophysical coverage as well as technological and socio-economic representation? Regional differences?
- Which changes are needed to current model frameworks/ecosystems? How do models have to change when new radical ideas would be implemented; with different concepts (circular economy, other business models, mobility as a services, housing as a service; vehicle retrofits, etc.)
- Describe how a model ecosystem can help understand the implications of low demand futures for industry, and what changes/additions/interfaces to existing models are needed. Are the system definitions fit for modeling the transformation?
- How do system boundaries change when new radical ideas would be implemented; with different concepts (circular economy, other business models, mobility as a services, housing as a service; vehicle retrofits, etc.). What about pro-sumers, which are social innovations in organizing production and consumption?
- Outlook and potential next steps? Develop an archive of models? E.g. extend on previous EU project who did that for IAMs? How to unearth and connect to earlier work on process-based macro-economics modelling from the 1990s?

Planned outcomes and conclusions from this section

- Map out an interdisciplinary industry model landscape
- Articulate key principles and rationales of the different modelling approaches, to help navigate increasingly diverse approaches and fields participating in LEMD modelling.
- Articulate and highlight critical links to other sectors/modelling approaches
- Refine industry modelling vision in light of EDITS and 1.5°C narrative
- Articulate research roadmap and identify promising synergies and potentials

References

Aguilar-Hernandez, G.A., Dias Rodrigues, J.F., Tukker, A., 2021. Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies. J. Clean. Prod. 278, 123421. https://doi.org/10.1016/j.jclepro.2020.123421

Brand-Correa, L.I., Martin-Ortega, J., Steinberger, J.K., 2018. Human Scale Energy Services: Untangling a 'golden thread.' Energy Res. Soc. Sci. 38, 178–187. https://doi.org/10.1016/j.erss.2018.01.008

Brand-Correa, L.I., Steinberger, J.K., 2017. A Framework for Decoupling Human Need Satisfaction From Energy Use. Ecol. Econ. 141, 43–52. https://doi.org/10.1016/j.ecolecon.2017.05.019

Carmona, L., Whiting, K., Carrasco, A., Sousa, T., Domingos, T., 2017. Material Services with Both Eyes Wide Open. Sustainability 9, 1508. https://doi.org/10.3390/su9091508

Creutzig, F., Callaghan, M., Ramakrishnan, A., Javaid, A., Niamir, L., Minx, J., Müller-Hansen, F., Sovacool, B., Afroz, Z., Andor, M., Antal, M., Court, V., Das, N., Díaz-José, J., Döbbe, F., Figueroa, M.J., Gouldson, A., Haberl, H., Hook, A., Ivanova, D., Lamb, W.F., Maïzi, N., Mata, É., Nielsen, K.S., Onyige, C.D., Reisch, L.A., Roy, J., Scheelbeek, P., Sethi, M., Some, S., Sorrell, S., Tessier, M., Urmee, T., Virág, D., Wan, C., Wiedenhofer, D., Wilson, C., 2021. Reviewing the scope and thematic focus of 100 000 publications on energy consumption, services and social aspects of climate change: a big data approach to demand-side mitigation *. Environ. Res. Lett. 16, 033001. https://doi.org/10.1088/1748-9326/abd78b

Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürge-Vorsatz, D., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. Nat. Clim. Change 8, 260–263. https://doi.org/10.1038/s41558-018-0121-1

Eurostat, 2012. Economy-wide Material Flow Accounts (EW-MFA). Compilation Guide 2012.

Fell, M.J., 2017. Energy services: A conceptual review. Energy Res. Soc. Sci. 27, 129–140. https://doi.org/10.1016/j.erss.2017.02.010

Fischedick, M., Roy, J., Amr Abdel-Aziz, Adolf Acquaye, Julian Allwood, Jean-Paul Ceron, Yong Geng, Haroon Kheshgi, Alessandro Lanza, Daniel Perczyk, Lynn Price, Estela Santalla, Claudia Sheinbaum, Kanako Tanaka, 2014. Chapter 10 - Industry, in: AR5 Climate Change 2014: Mitigation of Climate Change. Cambridge University Press.

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and Indicators of Economy-wide Material Flow Accounting: State of the Art and Reliability Across Sources. J. Ind. Ecol. 15, 855–876. https://doi.org/10.1111/j.1530-9290.2011.00366.x

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., Valin, H., 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat. Energy 3, 515. https://doi.org/10.1038/s41560-018-0172-6

Haberl, H., Dominik Wiedenhofer, Karl-Heinz Erb, Christoph Görg, Fridolin Krausmann, 2017. The Material Stock–Flow–Service Nexus: A New Approach for Tackling the Decoupling Conundrum. Sustainability 9, 1049. https://doi.org/10.3390/su9071049

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 2, 173–184. https://doi.org/10.1038/s41893-019-0225-2

Hardt, L., O'Neill, D.W., 2017. Ecological Macroeconomic Models: Assessing Current Developments. Ecol. Econ. 134, 198–211. https://doi.org/10.1016/j.ecolecon.2016.12.027

Jackson, T., Victor, P.A., 2019. Unraveling the claims for (and against) green growth. Science 366, 950–951. https://doi.org/10.1126/science.aay0749

Jax, K., Barton, D.N., Chan, K.M.A., de Groot, R., Doyle, U., Eser, U., Görg, C., Gómez-Baggethun, E., Griewald, Y., Haber, W., Haines-Young, R., Heink, U., Jahn, T., Joosten, H., Kerschbaumer, L., Korn, H., Luck, G.W., Matzdorf, B., Muraca, B., Neßhöver, C., Norton, B., Ott, K., Potschin, M., Rauschmayer, F., von Haaren, C., Wichmann, S., 2013. Ecosystem services and ethics. Ecol. Econ. 93, 260–268.

Kalt, G., Thunshirn, P., Wiedenhofer, D., Krausmann, F., Haas, W., Haberl, H., 2021. Material stocks in global electricity infrastructures – An empirical analysis of the power sector's stock-flow-service nexus. Resour. Conserv. Recycl. 173, 105723. https://doi.org/10.1016/j.resconrec.2021.105723

Kalt, G., Wiedenhofer, D., Görg, C., Haberl, H., 2019. Conceptualizing energy services: A review of energy and well-being along the Energy Service Cascade. Energy Res. Soc. Sci. 53, 47–58. https://doi.org/10.1016/j.erss.2019.02.026

Keyßer, L.T., Lenzen, M., 2021. 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. Nat. Commun. 12, 2676. https://doi.org/10.1038/s41467-021-22884-9

Krausmann, F., Lauk, C., Haas, W., Wiedenhofer, D., 2018. From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. Glob. Environ. Change 52, 131–140. https://doi.org/10.1016/j.gloenvcha.2018.07.003

Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S., Jackson, T., 2017. Material Flow Accounting: Measuring Global Material Use for Sustainable Development. Annu. Rev. Environ. Resour. 42. https://doi.org/10.1146/annurev-environ-102016-060726

Lamb, W.F., Steinberger, J.K., 2017. Human well-being and climate change mitigation: Human well-being and climate change mitigation. Wiley Interdiscip. Rev. Clim. Change 8, e485. https://doi.org/10.1002/wcc.485

Max-Neef, M.A., 1991. Human scale development : conception, application and further reflections - UQ eSpace [WWW Document]. URL https://espace.library.uq.edu.au/view/UQ:340489 (accessed 5.4.21).

McCarthy, A., Dellink, R., Bibas, R., 2018. The Macroeconomics of the Circular Economy Transition: A Critical Review of Modelling Approaches (OECD Environment Working Papers No. 130), OECD Environment Working Papers. https://doi.org/10.1787/af983f9a-en

Müller, D.B., Liu, G., Løvik, A.N., Modaresi, R., Pauliuk, S., Steinhoff, F.S., Brattebø, H., 2013. Carbon Emissions of Infrastructure Development. Environ. Sci. Technol. 47, 11739–11746. https://doi.org/10.1021/es402618m

OECD, 2008. Measuring Material Flows and Resource Productivity. Volume I. The OECD Guide. Organisation for Economic Co-Operation and Development, Paris, France.

Pauliuk, S., Arvesen, A., Stadler, K., Hertwich, E.G., 2017. Industrial ecology in integrated assessment models. Nat. Clim. Change 7, 13–20. https://doi.org/10.1038/nclimate3148

Pauliuk, S., Hertwich, E.G., 2015. Socioeconomic metabolism as paradigm for studying the biophysical basis of human societies. Ecol. Econ. 119, 83–93. https://doi.org/10.1016/j.ecolecon.2015.08.012

Pauliuk, S., Müller, D.B., 2014. The role of in-use stocks in the social metabolism and in climate change mitigation. Glob. Environ. Change 24, 132–142. https://doi.org/10.1016/j.gloenvcha.2013.11.006

Potschin-Young, M., Haines-Young, R., Görg, C., Heink, U., Jax, K., Schleyer, C., 2018. Understanding the role of conceptual frameworks: Reading the ecosystem service cascade. Ecosyst. Serv. 29, 428–440. https://doi.org/10.1016/j.ecoser.2017.05.015

Rao, N.D., Min, J., 2017. Decent Living Standards: Material Prerequisites for Human Wellbeing. Soc. Indic. Res. https://doi.org/10.1007/s11205-017-1650-0

Seto, K.C., Davis, S.J., Mitchell, R.B., Stokes, E.C., Unruh, G., Ürge-Vorsatz, D., 2016. Carbon Lock-In: Types, Causes, and Policy Implications. Annu. Rev. Environ. Resour. 41, 425–452. https://doi.org/10.1146/annurev-environ-110615-085934

Victor, P.A., 2012. Growth, degrowth and climate change: A scenario analysis. Ecol. Econ. 84, 206–212. https://doi.org/10.1016/j.ecolecon.2011.04.013

Victor, P.A., Rosenbluth, G., 2007. Managing without growth. Ecol. Econ. 61, 492–504. https://doi.org/10.1016/j.ecolecon.2006.03.022

Table 6: Bibliographic information on the literature identified and assessed so far.

Title	Year	Authors	Paper DOI/URL	Method
Feasible alternatives to green growth	2020	D'Alessandro et al.	https://doi.org/10.1038/s41893-020-0484-y	**1**
Coupling environmental transition and social prosperity: a scenario-analysis of the Italian case	2021	Cieplinski et al.	https://doi.org/10.1016/j.strueco.2021.03.007	**1**
Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries	2016	van Ruijen et al.	10.1016/j.resconrec.2016.04.016	**2**
An ecological macroeconomics model: The energy transition in the EU	2020	Nieto et al.	https://doi.org/10.1016/j.enpol.2020.111726	**1**
Providing decent living with minimum energy: A global scenario	2020	Millward-Hopkins et al.	https://doi.org/10.1016/j.gloenvcha.2020.102168	**7**
Shared socio-economic pathways and their implications for global materials use	2020	Schandl et al.	https://doi.org/10.1016/j.resconrec.2020.104866	**3**
Global Metal Use Targets in Line with Climate Goals	2020	Watari et al.	10.1021/acs.est.0c02471	**7**
Growing stocks of buildings, infrastructures and machinery as key challenge for compliance with climate targets	2020	Krausmann et al.	10.1016/j.gloenvcha.2020.102034	**7**
An integrated biophysical and economic modeling framework for long-term sustainability analysis: the HARMONEY model	2020	King	https://doi.org/10.1016/j.ecolecon.2019.106464	**1**
The scope for better industry representation in long-term energy models: Modeling the cement industry	2019	Kermeli et al	https://doi.org/10.1016/j.apenergy.2019.01.252	**5**
Pursuing necessary reductions in embedded GHG emissions of developed nations: Will efficiency improvements and changes in consumption get us there?	2018	Bjorn et al.	https://doi.org/10.1016/j.gloenvcha.2018.08.001	**6**
Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C	2020	Sharmina et al.	https://doi.org/10.1080/14693062.2020.1831430	**5**
Global scenarios of resource and emission savings from material efficiency in residential buildings and cars	2021	Pauliuk et al.	https://doi.org/10.1038/s41467-021-25300-4	**7**
Global greenhouse gas emissions from residential and commercial building	2021	Zhong et al.	https://doi.org/10.1038/s41467-021-26212-z	**7**

materials and mitigation strategies to 2060				
A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies	2018	Grübler et al.	https://doi.org/10.1038/s41560-018-0172-6	**7**
Global material requirements for the energy transition. An exergy flow analysis of decarbonisation pathways	2018	Valero et al.	https://doi.org/10.1016/j.energy.2018.06.149	**7**
Analysis of Potential for Critical Metal Resource Constraints in the International Energy Agency's Long-Term Low-Carbon Energy Scenarios	2018	Watari et al.	10.3390/min8040156	**2**
Macroeconomic modelling under energy constraints: Global low carbon transition scenarios	2020	Nieto et al.	10.1016/j.enpol.2019.111090	**1**
The Macroeconomics of the Circular Economy - Transition A CRITICAL REVIEW OF MODELLING APPROACHES	2018	McCarthy, Dellink and Bibas (OECD)	http://dx.doi.org/10.1787/af983f9a-en	**3**
Towards a circular economy: insights based on the development of the global ENGAGE-materials model and evidence for the iron and steel industry	2017	Winning et al.	10.1007/s10368-017-0385-3	**3**
Integrating Dynamic Material Flow Analysis and Computable General Equilibrium Models for Both Mass and Monetary Balances in Prospective Modeling: A Case for the Chinese Building Sector	2019	Cao et al.	DOI: 10.1021/acs.est.8b03633	**3**
Metal supply constraints for a low-carbon economy?	2018	de Koning et al.	10.1016/j.resconrec.2017.10.040	**4**
Energy modeling approach to the global energy-mineral nexus: a first look at metal requirements and the 2°C target	2017	Tokimatsu et al.	10.1016/j.apenergy.2017.05.151	**5**
The effect of additive manufacturing on global energy demand: An assessment using a bottom-up approach	2018	Verhoef et al.	https://doi.org/10.1016/j.enpol.2017.10.034	**6**
The sponge effect and carbon emission mitigation potentials of the global cement cycle	2020	Cao et al.	https://doi.org/10.1038/s41467-020-17583-w	**7**
Production, use, and fate of all plastics ever made	2017	Geyer et al.	https://doi.org/10.1126/sciadv.1700782	**7**
Resource Demand Scenarios for the Major Metals	2018	Elshkaki et al.	https://doi.org/10.1021/acs.est.7b05154	**3**

A global circular economy scenario in a multi-regional input-output framework	2019	Wiebe et al.	http://dx.doi.org/10.1021/acs.est.9b01208	**4**
Energy Technology Perspectives	2021	IEA	https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf	**5**
Taking Stock of Built Environment Stock Studies: Progress and Prospects	2019	Lanau et al.	https://doi.org/10.1021/acs.est.8b06652	**10**
1.5 °C degrowth scenarios suggest the need for new mitigation pathways	2021	Keyßer and Lenzen	https://doi.org/10.1038/s41467-021-22884-9	**9**
Growth, degrowth and climate change: A scenario analysis	2012	Victor	https://doi.org/10.1016/j.ecolecon.2011.04.013	**1**
Modelling industry energy demand using multiple linear regression analysis based on consumed quantity of goods	2021	Maaouane et al.	https://www.sciencedirect.com/science/article/pii/S0360544221005193?via%3Dihub	**2**
Scenarios towards limiting global mean temperature increase below 1.5 °C	2018	Rogelj et al.	https://www.nature.com/articles/s41558-018-0091-3	**5**
Enhancing recycling of construction materials: An agent based model with empirically based decision parameters	2014	Knoeri, et al.	https://eprints.whiterose.ac.uk/82726/	**8**
Critical materials in global low-carbon energy scenarios: The case for neodymium, dysprosium, lithium, and cobalt.	2020	Junne et al.	https://doi.org/10.1016/j.energy.2020.118532	**7**
Growing stocks of buildings, infrastructures and machinery as key challenge for compliance with climate targets	2020	Krausmann et al.	10.1016/j.gloenvcha.2020.102034	**7**
The Environmental Impact of Green Consumption and Sufficiency Lifestyles Scenarios in Europe: Connecting Local Sustainability Visions to Global Consequences	2019	Vita et al.	https://doi.org/10.1016/j.ecolecon.2019.05.002	**4**
Transformation of India's steel and cement industry in a sustainable 1.5 °C world	2020	Dhar et al.	https://doi.org/10.1016/j.enpol.2019.111104	**7**
Industry evolution, rational agents and the transition to sustainable electricity production	2011	Safarzynska et al.	https://doi.org/10.1016/j.enpol.2011.07.046	**8**

Enabling energy system transition toward decarbonization in Japan through energy service demand reduction	2021	Oshiro et al.	https://doi.org/10.1016/j.energy.2021.120464	**5**
Modelling industry energy demand using multiple linear regression analysis based on consumed quantity of goods	2021	Maaouane et al.	https://doi.org/10.1016/j.energy.2021.120270	**2**
Incorporating critical material cycles into metal-energy nexus of China's 2050 renewable transition	2019	Wang et al.	https://doi.org/10.1016/j.apenergy.2019.113612	**6**
Energy Efficiency Vision 2050: How will new societal trends influence future energy demand in the European countries?	2021	Brugger et al.	https://doi.org/10.1016/j.enpol.2021.112216	**9**
Towards net zero nutrition: The contribution of demand-side change to mitigating UK food emissions	2020	Garvey et al.	https://doi.org/10.1016/j.jclepro.2020.125672	**4**
Social and environmental analysis of food waste abatement via the Peer-to-Peer Sharing Economy	2020	Makov et al.	https://www.nature.com/articles/s41467-020-14899-5	**6**
Impacts of ride and car-sharing associated with fully autonomous cars on global energy consumptions and carbon dioxide emissions	2021	Akimoto et al.	https://doi.org/10.1016/j.techfore.2021.121311	**5**
A race to zero - Assessing the position of heavy industry in a global net-zero CO2 emissions context	2021	van Sluisveld et al.	https://doi.org/10.1016/j.egycc.2021.100051	**5**
Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models	2017	Edelenbosch et al.	http://dx.doi.org/10.1016/j.energy.2017.01.017	**5**
Inside the Black Box: Understanding key drivers of global emission scenarios	2018	Koomey et al	10.1016/j.envsoft.2018.08.019	
Environmental Implications of Future Demand Scenarios for Metals Methodology and Application to the Case of Seven Major Metals	2018	Van der Voet et al	DOI: 10.1111/jiec.12722	
Waste energy recovery and energy efficiency improvement in China's iron and steel industry	2017	Zhang et al.	https://doi.org/10.1016/j.apenergy.2017.01.072	
Modeling technological changes and its impact on energy savings in the US iron and steel sector	2017	Karali et al.	http://dx.doi.org/10.1016/j.apenergy.2017.05.173	

Quantifying the impacts of decarbonisation in China's cement sector: A perspective from an integrated assessment approach	2016	Li et al.	http://dx.doi.org/10.1016/j.apenergy.2015.12.112	
Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm	2017	van Vuuren et al.	http://dx.doi.org/10.1016/j.gloenvcha.2016.05.008	
Drawdown (review)	2017/2020	Hawken, P. (ed.)/Wilkinson, K. (ed.)	https://drawdown.org/sectors/industry ; https://drawdown.org/sites/default/files/pdfs/TheDrawdownReview%E2%80%932020%E2%80%93Download.pdf	
A Framework for Modelling Consumption-Based Energy Demand and Emission Pathways	2020	Mastrucci et al.	https://dx.doi.org/10.1021/acs.est.9b05968	
Contraction and convergence of in-use metal stocks to meet climate goals	2021	Watari et al.	https://doi.org/10.1016/j.gloenvcha.2021.102284	**7**
Modelling deep decarbonization of industrial energy consumption under 2-degree target: Comparing China, India and Western Europe	2019	Wang and Chen	https://doi.org/10.1016/j.apenergy.2019.01.131	**5**
Comprehensive assessment of energy conservation and CO2 emissions mitigation in China's iron and steel industry based on dynamic material flows	2018	Zhang et al	http://dx.doi.org/10.1016/j.apenergy.2017.10.084	**7**
LowGrow SFC: a stock-flow-consistent ecological macroeconomic model for Canada	2019	Jackson & Victor	http://cusp.ac.uk/themes/aetw/wp16/	**1**
The Transition to a Sustainable Prosperity-A Stock-Flow-Consistent Ecological Macroeconomic Model for Canada	2020	Jackson & Victor	https://doi.org/10.1016/j.ecolecon.2020.106787	**1**
A stock-flow-fund ecological macroeconomic model	2017	Dafermos et al.	https://doi.org/10.1016/j.ecolecon.2016.08.013	**1**
Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28	2020	Ciacci et al.	https://doi.org/10.1016/j.gloenvcha.2020.102093	**2 + 6 (based on 7)**

Material-energy-water nexus: Modelling the long term implications of aluminium demand and supply on global climate change up to 2050	2020	Elshkaki et al.	https://doi.org/10.1016/j.envres.2019.108964	**2 + 7**
Comprehensive assessment of energy conservation and CO2 emission reduction in future aluminum supply chain	2022	Tian et al.	https://doi.org/10.1016/j.apenergy.2021.117796	**7**
Modeling copper demand in China up to 2050	2019	Dong et al.	https://onlinelibrary.wiley.com/doi/10.1111/jiec.12926	**7**
Quantifying the co-benefits of decarbonisation in China's steel sector: An integrated assessment approach	2016	Ma et al	http://dx.doi.org/10.1016/j.apenergy.2015.08.005	**5 + 7**
A bottom-up optimization model for long-term CO 2 emissions reduction pathway in the cement industry: A case study of China	2016	Xu et al	http://dx.doi.org/10.1016/j.ijggc.2015.11.028	**5**
Improving material projections in Integrated Assessment Models: The use of a stock-based versus a flow-based approach for the iron and steel industry	2021	Kermeli et al	https://doi.org/10.1016/j.energy.2021.122434	**5 + 7**
The Roles of Energy and Material Efficiency in Meeting Steel Industry CO_2 Targets	2013	Milford et al	https://doi.org/10.1021/es3031424	**7**
The critical role of the industrial sector in reaching long-term emission reduction, energy efficiency and renewable targets	2015	Fais et al	https://doi.org/10.1016/j.apenergy.2015.10.112	**5**
The Circular Economy and Benefits for Society Jobs and Climate Clear Winners in an Economy Based on Renewable Energy and Resource Efficiency	2017	Wijkman et al	https://clubofrome.org/wp-content/uploads/2020/03/The-Circular-Economy-and-Benefits-for-Society.pdf	**4**
Indirect CO2 Emission Implications of Energy System Pathways:Linking IO and TIMES Models for the UK	2015	Daly et al	https://doi.org/10.1021/acs.est.5b01020	**5 + 4**
A bottom-up analysis of China's iron and steel industrial energy consumption and CO2 emissions	2014	Chen et al	https://doi.org/10.1016/j.apenergy.2014.06.002	**5+7**
Global critical materials markets: An agent-based modeling approach	2015	Riddle et al	https://doi.org/10.1016/j.resourpol.2015.01.002	**8**
Testing Scenarios to Achieve Workplace Sustainability Goals Using Backcasting and Agent-Based Modeling	2016	García-Mira et al	https://doi.org/10.1177/0013916516673869	**8**

Requirements Engineering for an Industrial Symbiosis Tool for Industrial Parks Covering System Analysis, Transformation Simulation and Goal Setting	2020	Lütje and Wohlgemuth	https://doi.org/10.3390/admsci10010010	**8**
A Stochastic Approach to Model Dynamic Systems in Life Cycle Assessment	2013	Miller et al	https://doi.org/10.1111/j.1530-9290.2012.00531.x	**8**
A time-series material-product chain model extended to a multiregional industrial symbiosis: The case of material circularity in the cement sector	2021	Lessard et al	https://doi.org/10.1016/j.ecolecon.2020.106872	5+7
Steel in a circular economy: Global implications of a green shift in China	2021	Nechifor et al	https://doi.org/10.1016/j.worlddev.2019.104775	**3**

Research Report

The effectiveness of energy and climate policy for reducing fossil CO_2 emissions in energy demand sectors.

Prepared for:

Research Institute of Innovative Technology for the Earth (RITE), Kyoto, Japan, as part of the EDITS project on Energy Demand changes Induced by Technological and Social innovations.

Prepared by:

Dr Theodoros Arvanitopoulos

Professor Charlie Wilson

Tyndall Centre for Climate Change Research, University of East Anglia (UEA) on behalf of UEA Consulting Ltd, Norwich, United Kingdom.

Date:

28 February 2022

Acknowledgements:

The authors gratefully acknowledge the policy data compiled and coded by Dr Simon Schaub (Heidelberg University, Germany), advice on IEA energy and emission statistics from Jan Ivar Korsbakken (CICERO, Norway), and advice on econometric modelling from Nicholas Vasilakos (University of East Anglia, UK). The analysis in this report is original unpublished work funded by RITE through the EDITS project, for which the authors are very grateful.

The effectiveness of energy and climate policy for reducing fossil CO_2 emissions in energy demand sectors.

Theodoros Arvanitopoulos [1]

Charlie Wilson [1 2 3 *]

Simon Schaub [4]

Nicholas Vasilakos [1]

[1] *University of East Anglia, UK*

[2] *University of Oxford, UK*

[3] *International Institute for Applied Systems Analysis, Austria*

[4] *University of Heidelberg, Germany*

** corresponding author: wilsonch@iiasa.ac.at*

Abstract

In this study we empirically assess the effectiveness of energy and climate policies for reducing fossil CO_2 emission reductions in OECD countries and major developing economies over the period 2000-2018. We estimate regression models with country and year fixed effects, with emission intensity (CO_2/GDP) as our dependent variable, policies as our independent variables, and a range of political, economic, and geographic controls. For our independent variables we distinguish the effects of policy density, policy instrument types, and sectoral policy coverage, focusing on energy demand sectors.

At the country level, we find that higher policy density (cumulative total numbers of policies) is associated with larger reductions in emissions intensity. We also find that a greater specialisation in policy instrument types (regulatory, market-based, voluntary) is associated with larger reductions in emissions intensity.

At the sectoral level, we find that a greater specialisation of sectoral policies in emissions-intensive sectors is associated with larger reductions in emissions intensity. Exploring this sectoral result further, we find that higher policy density in each of the buildings, industry and transport sectors is associated with larger reductions in emissions intensity (sectoral CO_2/GGP), but this effect is not statistically significant for buildings as emission reductions are picked up indirectly in the upstream electricity generation sector.

Overall, we provide robust and generalisable (cross-country) empirical evidence that more sectoral policies help reduce fossil CO_2 emission intensity in energy demand sectors, after controlling for a wide variety of other effects on emissions. Climate policies in energy demand sectors are effective for reducing emissions in OECD and major developing economies.

1. Introduction

A growing corpus of national laws and policies has been implemented to reduce greenhouse gas (GHG) emissions in line with international climate targets. The Kyoto Protocol in 1997 included binding emission-reduction targets for developed 'Annex 1' countries. The Paris Agreement in 2015 broadened the scope of emission-reduction commitments or 'Nationally Determined Contributions' (NDCs) to all country signatories. According to the Net Zero

Tracker[1], 136 countries now have pledged net-zero targets over timescales from 2035 (e.g., Finland) to 2070 (e.g., India), albeit with varying levels of commitment. These net-zero pledges cover 88% of global GHG emissions, and 90% and 85% of the world's GDP and population respectively (Hale et al., 2021).

Climate policy plays a critical role in translating emission-reduction commitments into declining emission trends. The portfolio of climate policies implemented to-date is diverse, ranging from carbon taxes and emission trading schemes for setting market incentives, to performance and technology standards for regulating emitting activity, and to education, campaigns, and information disclosure supporting 'soft' or voluntary progress on emission reductions.

New or reformed climate governance institutions also support the design, implementation, and enforcement of specific climate policies. In the UK, for example, the 2008 Climate Change Act established an independent advisory body, the Committee on Climate Change, for holding government to account on progress towards legally-binding emission reduction targets that were introduced in the same legislation (Lockwood, 2013). The Committee on Climate Change has increasingly developed a distinctive identity as a governance institution shaping national climate policy in the UK, as have other analogous bodies in other countries (Dudley et al., 2021).

Climate policies and institutions with explicit emission-reduction objectives sit alongside a longer history of energy policies that directly or indirectly affect emitting activities in both the energy supply (e.g., power generation) and in energy end-use sectors (e.g., building efficiency). Since the 1970s oil shocks, successive waves of energy policies have sought to reduce import dependence on energy commodities, control air pollution, deregulate and liberalise traditional monopoly industries, support nascent renewable energy industries, and so on. In the past two decades, decarbonisation has been a principal driver of change in the energy sector, such that the lines between climate policy and energy policy have become increasingly blurred.

1.1. Do climate policy and governance institutions work?

There are many criteria by which to assess policy effectiveness including efficiency, fairness, tractability, but in a climate context, there is one ultimate outcome criterion: emission reductions. In this paper, we empirically test whether climate policy and governance institutions have proved effective at reducing emissions to-date. We focus specifically on fossil CO_2 emissions which account for around two thirds of total greenhouse gas (GHG) emissions.

In 2020, total global fossil CO_2 emissions totalled 34.8 billion tonnes of which 40% were from the combustion of coal, 32% oil, 21% gas, with 5% from cement production, and 2% from flaring and other sources (GCP, 2021). Developed (OECD) and major emerging economies (BRIICS) accounted for 80.6% of this total, broken down as 32.7% OECD + 31.6% China + 16.4% Brazil, Russia, Indonesia, India, South Africa (GCP, 2021). Gross CO_2 emissions globally from land-use change (e.g., deforestation) are around 14 billion tonnes, offset by around 10 billion tonnes of CO_2 removals (e.g., abandoned agricultural land) for a net land-use contribution to total territorial CO_2 emissions of around 4 billion tonnes in 2020 (GCP, 2021).

Our central expectation is that countries with more rapidly declining fossil CO_2 emissions have more dense and diverse policy frameworks across both energy supply and demand

[1] https://zerotracker.net

sectors. This is based on existing literature, particularly Le Quéré et al. (2020) and Eskander & Fankhauser (2020).

In their study of 18 developed economies that had successfully peaked and declined their fossil CO_2 emissions over the period 2005-2015, Le Quéré et al. (2020) found a significant association between total numbers of climate policies per country and declining emission trends in absolute terms. By decomposing emissions into different supply and demand factors, Le Quéré et al. (2020) further showed that falling energy demand (partly explained by slower GDP growth) and the displacement of fossil fuels by renewable energy were the main drivers of declining emissions in the 18 peak-and-decline countries, but not elsewhere. This provided generalisable (multi-country) correlational evidence of the effectiveness of energy efficiency and renewable energy policies for reducing fossil CO_2 emissions.

Eskander & Fankhauser (2020) used panel regressions with country and year fixed effects to test the effect of climate policies on GHG emissions intensity (CO_2/GDP and nonCO_2 GHGs/GDP) in a larger sample of 133 countries over the period 1999-2016. By using emissions intensity rather than absolute emissions, they reduced the potentially confounding effect of country size and economic performance. Their models also controlled for other main effects on emissions intensity including economic structure and development stage (e.g., GDP per capita, imports as % of GDP, services as % of GDP), governance conditions (e.g., rule of law, federal vs. unitary), and geography (e.g., weather fluctuations). Eskander & Fankhauser (2020) found that each new climate law reduced emissions intensity by 0.8% in the short-term and 1.8% in the long-term, with the generalisable effect dominated by parliamentary acts and countries with a strong rule of law. In subsequent analysis for Carbon Brief, they found that 12% of the emission reductions in the G7 countries over the 1999-2016 period could be attributed to climate policies rather than external socioeconomic forces and market trends.[2]

1.2. Policy density

Are more climate policies always better? From a normative standpoint, the 'Tinbergen rule' applies Occam's razor to public policy: the lowest possible number of policy instruments should be used to address a particular problem, i.e., one policy per objective (Knudson, 2009). However, interactions between policy goals and sectors, complex policy design processes, and diverse political economic interests, mean that policy packages or portfolios are more common in the real world (del Rio & Howlett, 2013).

From a political economic perspective, Pahle et al. (2018) argue that an accumulative sequencing of climate policies is useful for incrementally relaxing or removing barriers to climate action over time, and so helps improve climate policy effectiveness. Barriers may be economic (e.g., non-cost-effective policy impact assessments), distributional (e.g., interest group opposition), institutional (e.g., lack of governance expertise), or misaligned incentives (e.g., free riding).

Schaffer et al. (2021) test whether legislative activity is responsive to public demand for climate action by regressing measures of issue salience and issue opinion on the number of new climate policies in a given year, controlling for cumulative total policy 'stock'. Their findings suggest a path dependency rather than a saturation effect in climate policymaking as countries that introduce more climate policies at a given point in time are more rather than less likely to adopt climate policies thereafter.

[2] https://www.carbonbrief.org/guest-post-g7-climate-laws-cut-emissions-by-1-3bn-tonnes-in-2019

Both political science and empirical analysis of large country samples define our first general expectation:

> *countries with more rapidly declining emissions have higher policy densities (cumulative total numbers of climate policies)*

Can this basic relationship be further distinguished by types of policy instrument or by sectoral policy coverage?

1.3. Policy instrument types

Climate policies are introduced through legislation that may involve many different policy instruments. Sterner & Coria (2013) use a taxonomy of eight basic instrument types: regulation, market-based, legal, informational, direct provision, voluntary, planning, and monitoring. Other taxonomies extend the characterisation of instruments to include also policy themes and target groups (Russo & Pavone, 2021).

With respect to climate change and other global policy problems of the Anthropocene, Sterner et al. (2019) argue for selecting and designing policies for specific societal and political contexts, with instrument choices carefully matched to clearly diagnosed socioeconomic problems. Put differently, there is no one-size-fits-all or 'first best' approach, despite the theoretical appeal of a harmonised global carbon price on grounds of economic efficiency.

Policy mixes can overcome distinct but interrelated barriers to progress towards policy goals, particularly if these are broadly defined as in the case of emission reductions. In other words, policy mixes matter as there are commonly a variety of market, innovation, or system failures to be overcome (OECD, 2015; Wilson & Kim, 2018), and these failures involve many different actors, interests, and political economic influences (Kivimaa & Kern, 2016).

In a recent empirical test of the largely theoretical arguments on policy mixes, Schmidt & Sewerin (2019) measure change over time in the renewable energy policy mixes of nine OECD countries, including instrument types as well as other design features such as technological specificity. Using a taxonomy of nine instrument types, they find countries generally have diverse and balanced policy mixes that are fairly stable over time, but with the dominant instrument type varying by country (e.g., financial instruments and framework policies in Canada and Germany). They then test the effect of different policy mix dynamics on renewable energy deployment as the ultimate outcome criterion for policy effectiveness. They find a significant but negative effect of balance on total renewable energy capacity, pointing to the effectiveness of more specialisation in instrument types. They conclude that the balance of instrument types is a relevant policy mix characteristic deserving more systematic attention (Schmidt & Sewerin, 2019).

Conversely, in their review of induced innovation or 'demand-pull' policy instruments, Grubb et al. (2021) find a positive association between mixes of interacting policies and innovation outcomes. However, they caution that this is contingent on national characteristics and regulatory contexts, particularly for natural monopolies like electricity networks.

The term 'policy mix' in the innovation literature means a mix of different instruments implemented in various contexts that may span single or multiple themes and groups of beneficiaries (OECD, 2010; Russo & Pavone, 2021). Here, we use the narrower definition restricted just to instrument type.

The theoretical and empirical literature on instrument diversity within policy mixes provides our second general expectation:

countries with more rapidly declining emissions use more diverse mixes of policy instruments (market-based, regulatory, and voluntary)

1.4. Sectoral coverage of policies

In the total stock of climate policies, economy-wide instruments such as carbon taxes are the exception rather than the norm. Many policies target sectoral activity either in the energy supply industry (resource extraction, electricity generation, refining) or in energy-using sectors (buildings, transport, industry). Emissions sources per country also vary widely by sector, with key determinants being the fossil intensity of electricity generation, transport modes and distances travelled, heating and cooling needs in the building stock, and economic structure including the presence of energy-intensive industries. The effectiveness of climate policies for reducing fossil CO_2 emissions should therefore vary as a function of how well the policy mix covers emitting sectors, with a greater policy commitment demonstrated by more policies targeting all emission sources and sectors.

This defines our third general expectation:

countries with more rapidly declining emissions have more diverse sectoral policy coverage (policy density per sector, weighted by sectoral emissions)

1.5. Climate governance institutions

In addition to these expectations on the effectiveness of climate policy density, instrument type, and sectoral coverage for reducing emissions, we note the importance of also testing the role of climate governance institutions. Long-term emission-reduction targets enshrined in law, dedicated climate ministries, and independent oversight bodies help create institutional direction, momentum, stability, and credibility that in turn shape the effectiveness of climate policy. These variables lie outside the scope of the current study but are an important topic for further research.

1.6. Aims & contributions of this study

The aim of this study is to empirically assess the effectiveness of energy and climate policies for reducing fossil CO_2 emission reductions historically, distinguishing the effects of policy density, policy instrument diversity, and sectoral policy coverage. Our study contributes to and extends existing literature in three important ways.

First, we develop, use, and make available a comprehensive policy dataset for 38 OECD and 6 BRIICS countries over the period 2000-2019 based mainly on IEA databases. We code each new climate-related legislations and policies in our dataset by instrument type and by target sector.

For instrument type, we use the taxonomy of eight instrument types from Sterner & Coria (2013). For target sector, we use the standard set of two energy supply sectors (energy industry own-use, and electricity and heat conversion) and three energy end-use sectors (buildings, transport, industry) used for energy and emission reporting by IEA, UNFCCC, and others. This gives us a highly granular set of time-series variables for 44 countries providing consistent measures of policy density, instrument type diversity, and sectoral policy coverage. For comparison, Eskander & Fankhauser (2020) use the more restrictive Climate Change Laws of the World database and only policy density variables, and Schmidt & Sewerin (2019) focus only on renewable energy policies.

Second, we use this new policy dataset to test discrete hypotheses on the effectiveness of policy density, instrument type diversity, and sectoral policy coverage on fossil CO_2

emissions, before combining insights into an overall model of CO_2 emission intensity trajectories over time.

Third, we further explore the effect of energy and climate policies on emission outcomes in specific sectors, focusing particularly on differences between energy end-use sectors (buildings, industry, transport) and the energy supply. This contributes to long-standing debates on the relative importance of energy-efficiency and other demand-side policies that help downsize the scale of the decarbonisation challenge (Grubler et al., 2018; Mundaca et al., 2019).

We use these empirical and analytical contributions to draw generalisable insights on the effectiveness of climate policy for reducing fossil CO_2 emissions.

2. Data

2.1. Climate policies

We obtained information on past and existing climate policies from the International Energy Agency (IEA) Policies and Measures Database (PMD). The IEA PMD dataset reports mainly past and existing government energy-related climate policies and measures across the world. Data on climate policies are supplied by various sources such as governments, partner organisations and the IEA itself. This dataset comprises mainly climate policies targeting emission reductions, energy efficiency improvements, and deployment of renewable and clean technologies. It covers data from 2000 onwards and provides detailed information on the name of policies, country of implementation, and the exact start date.

Eskander & Fankhauser (2020) employ in their study the Climate Change Laws of the World Database (CCLW) to construct their long-term and short-term policy density variables. Selection of policies for the CCLW database is based on legal documents, so it is particularly useful for assessing climate policy dynamics at a global level (Schaub et al., 2022). However, a key limitation CCLW captures only active climate laws and not those that have been repealed (Eskander & Fankhauser, 2020). In contrast, the IEA PMD has more extensive coverage of whole climate laws and provides in depth information on policy instrument types. As a result, the PMD reports a larger number of climate policies and is more suitable for assessing policy design for individual countries as it includes information on policy instrument types and sectoral coverage.

Using the IEA PMD, we analysed a total of 2,909 past and existing policies for OECD and BRIICS countries over the period 2000-2018, and coded the individual characteristics of each policy in terms of instrument type and sectoral coverage. We included all countries that are currently OECD members, including those that joined recently (e.g., Latvia in 2018, Costa Rica in 2021). The BRIICS countries are six major non-OECD economies: Brazil, Russia, India, Indonesia, China, and South Africa.

Our total sample of 2,909 policies for 44 countries over the period 2000-2018 is approximately three times larger than the sample of 1,092 climate laws used in Eskander & Fankhauser (2020) even though this covered 133 countries (both developed and developing) over a similar 18 year period from 1996-2016. As noted, this is because the IEA PMD is more extensive, and because the CCLW database omits past climate laws that have been repealed.

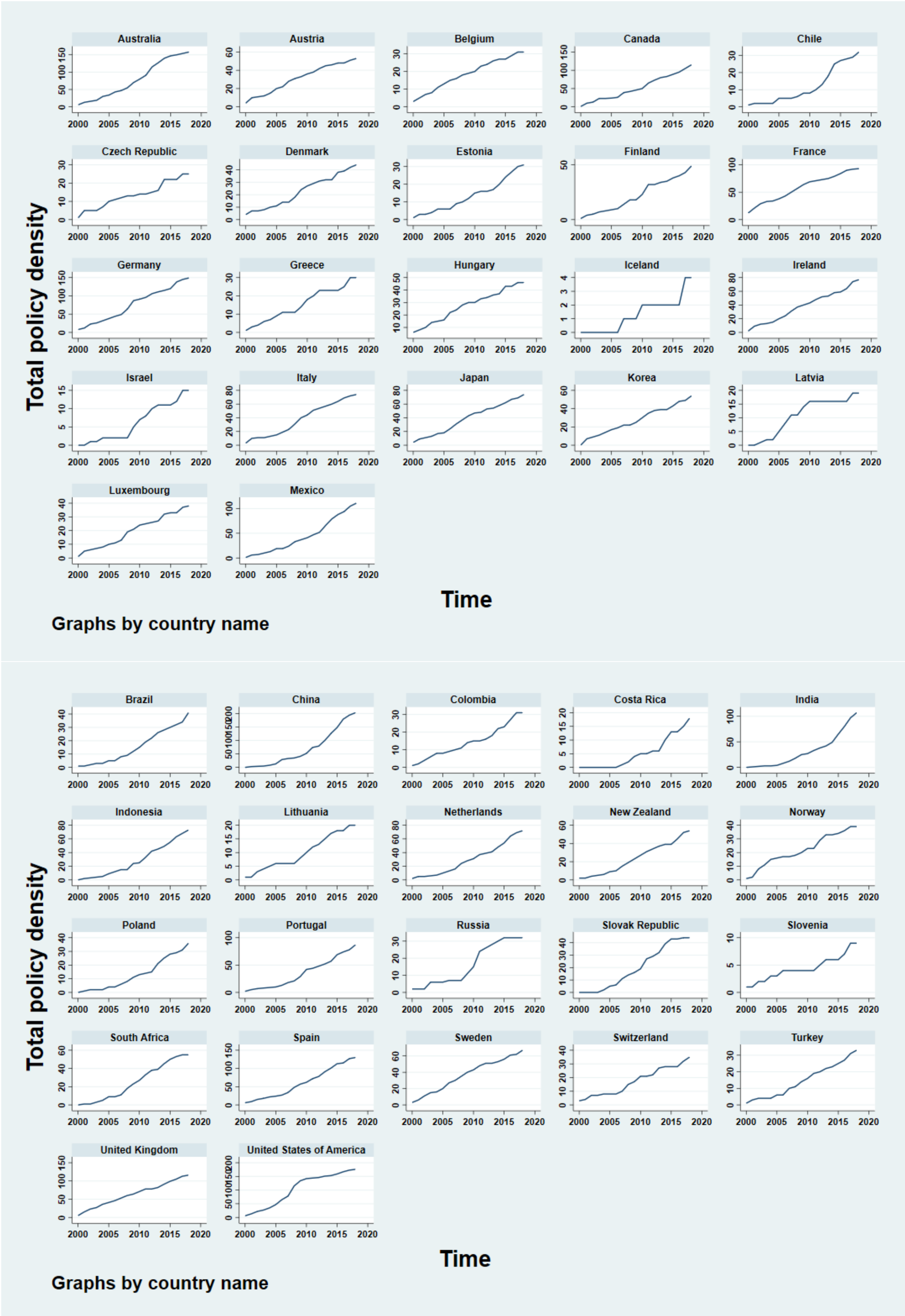
2.2. Policy density

Policy density, a concept introduced by Knill et al. (2012), measures either the total number of policies or policy instruments. We use information on climate policies in the IEA PMD to construct our basic annual policy density variable which captures the number of climate policies implemented within a country in any given year. As past policies should continue to have an effect on emission reduction in years following their implementation, we use annual policy density to generate cumulative total policy density such that all past (*t-1*, *t-2*, …) and current (*t*) climate policies are counted at year *t* within each country. This allows us to control for the cumulative effect of past and existing climate policies on fossil CO_2 emissions over long-term periods.

Figure 1 shows line plots of total policy density by country over time, showing clear upward trends for all countries in our dataset. Wider legislation of climate policies can be observed in the years following 2006. The BRIICS economies along with certain OECD countries (Chile, Israel, Italy, Lithuania) have been slow to start, but experienced a rapid increase in the overall number of climate policies from 2007 and onwards. The rest of the OECD countries have displayed more gradual adoption of climate policies over time. Focusing specifically on BRIICS, we observe that they experience an even steeper upward trend for total policy density from 2010 onwards. China is an important outlier given it has legislated annually a very large number of climate policies but mainly since 2011: e.g., 22 policies in 2011, 26 in 2014, and 31 in 2016. By 2018, countries with the largest numbers of climate policies are China, USA, Australia, UK, Canada, and Spain. China is the only country from the block of BRIICS economies that closely follows the larger OECD countries in terms of total policy density.

As our analysis runs from 2000-2018, initial policy densities in all countries are set to zero in 2000. Although most policies have been implemented since then, some countries including Australia, Denmark, Finland, Korea, and Norway had introduced significant numbers of policies before 2000. As a robustness test, we re-estimated our baseline regression model including initial conditions in the policy density variable (i.e., each country's cumulative total numbers of policies before 2000). We found no change in the model results or coefficients for the period 2000-2018.

Figure 1. Cumulative total policy density per country from 2000 - 2018, with countries split between upper and lower panel to aid visualisation.



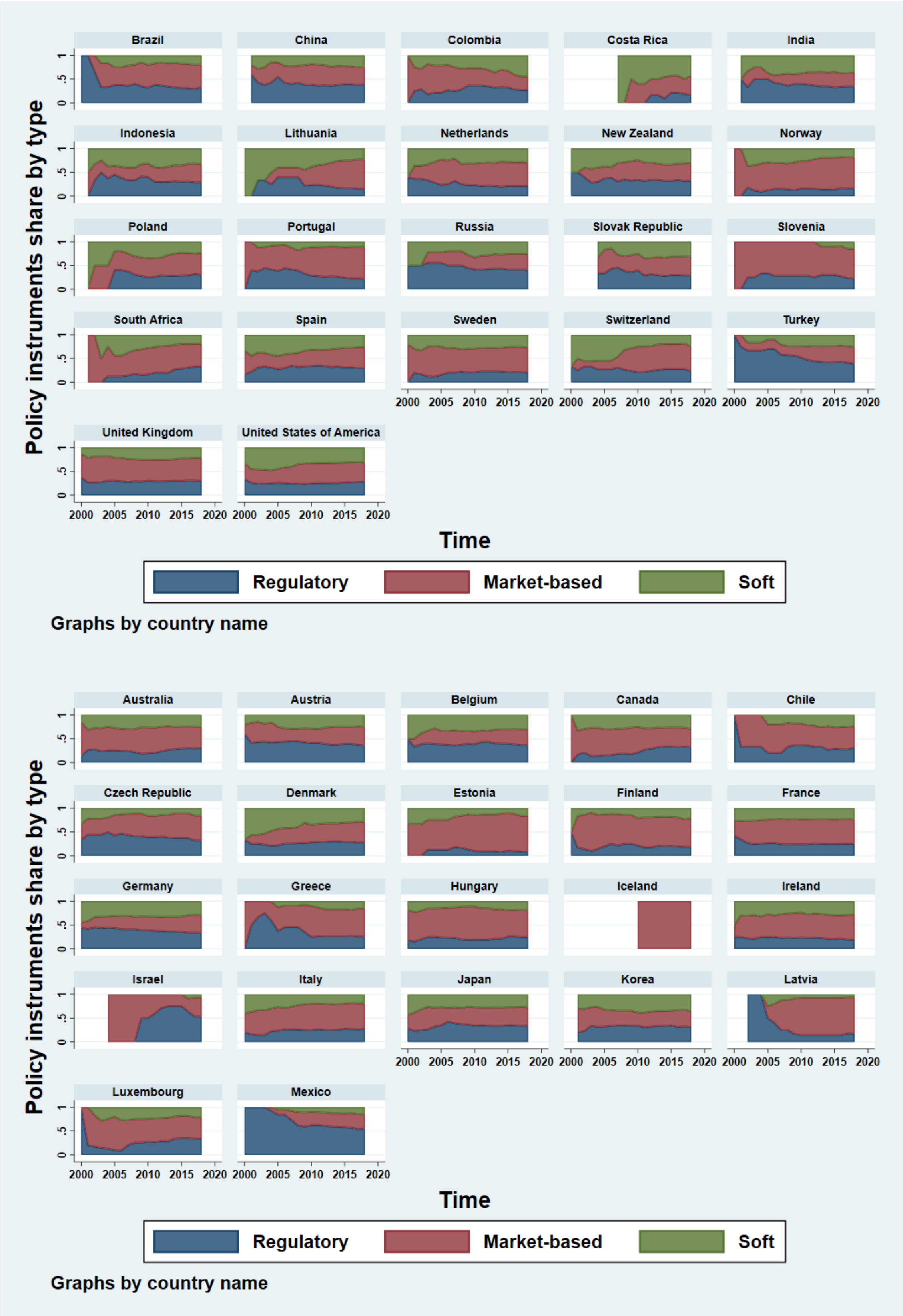
2.3. Policy instrument types

We use detailed information from the IEA PMD to classify policy instruments as belonging to one of eight types: legal, monitoring, regulatory, market-based, provisional, information, planning, and voluntary. To reduce complexity, we then aggregated these eight types into three overarching categories that are commonly used (Carley & Miller, 2012):

a. *Regulatory policies* (incorporating legal, monitoring, and regulatory policy instruments)
b. *Market-based policies* (incorporating market-based, and provisional policy instruments)
c. *Soft policies* (incorporating information, planning, and voluntary policy instruments)

The first category incorporates regulatory policy instruments and consists of all climate policies characterized as 'hard' regulation. The second category incorporates economic policy instruments includes those related to the provision of financial funds. The third category consists of 'soft' policies that are informational, voluntary, or are otherwise not legally binding. Figure 2 shows stacked plots of the shares of these three policy instrument categories in total policy density.

Figure 2. Policy instrument types as shares of total policy density, with countries split between upper and lower panel to aid visualisation.



To capture the diversity or specialisation of instrument types within any given country, we constructed a measure of diversity called the *Herfindahl-Hirschman Index (HHI).* The HHI is widely used in the economic literature to measure the market share of firms within sectors, labour specialisation within economies, and so on (Ginevičius & Čirba, 2007). We construct the HHI for each country by taking the sum of squares of the share of policy instrument types within the total policy density. We do this for both the full taxonomy of eight instrument types, and for the more aggregated three instrument categories. A higher value of the HHI indicates lower policy instrument diversity, and by extension, a higher level of specialisation on a particular policy instrument type. Conversely, a lower value of the HHI indicates higher policy instrument diversity and so lower specialisation on a particular policy instrument type. By using total policy density, we control for the cumulative (long-term) effect of policy instrument specialisation on changes in fossil CO_2 emissions. We expect that both our three and eight instrument HHIs should have a comparable effect on historical emissions, but we include both as a robustness check on our methodology. As our policy density variable begins at zero in 2000, we lack information on instrument type diversity before that date.

2.4. Sectoral policy coverage

We use information from the IEA PMD to classify climate policies as covering emitting activity in one of six sectors: electricity and heat production, energy industry own use, manufacturing and construction, buildings, transport, and agriculture. These six sectors match those used by IEA in its disaggregated reporting of fossil CO_2 emissions. We classified economy-wide or multi-sector policies as covering each of the relevant sectors. Policies not matched to any sector or sectors are classified as economy-wide policies only and comprise 2% of the total sample.

As for policy instrument types, we then construct an HHI to measure the level of specialisation of policies on particular sectors. In addition, we construct a weighted HHI for sectoral policies that gives higher weight to policies in those sectors with a larger share of total emissions in that country. This allows us to test whether specialising in policies targeting emission-intensive sectors has a larger effect.

As our policy density variable begins at zero in 2000, we lack information on sectoral policy coverage before that date.

Figure 3 shows that the sectoral distribution of sectoral policies among countries is not uniform. Policies covering the electricity and heat production sector, and the energy industry own use sector, are more common over the period 2000-2009 after which sectoral coverage becomes more diverse with policies increasingly targeting energy demand as well as supply. Exceptions to this pattern include Chile and Israel, and to a lesser extent, Brazil, and Poland. These countries have specialised in policies for the energy supply sector throughout the full time period. Sectoral policy coverage in energy demand sectors has been more mixed, with no uniform patterns across countries and over time.

Figure 3. Policy instruments by sector as a share of total policy density, with countries split between upper and lower panel to aid visualisation.

2.5. Fossil CO_2 emissions

We obtain data on historical fossil CO_2 emissions from the IEA CO_2 Emissions From Fuel Combustion database. This is probably the most comprehensive dataset on CO_2 emissions as it covers CO_2 emissions by sector and by fuel at a highly disaggregated level for almost all countries from 1990 to 2018 (IEA, 2018). We use this dataset to measure historical fossil CO_2 emission for the OECD and BRIICS countries at both national and sectoral level.

Overall, fossil CO_2 emissions for the BRIICS countries have been trending upwards from 2000 to roughly 2015, after which growth rates to 2018 have slowed. In contrast, European Union (EU) countries (with Poland as an exception), along with the UK and USA, have seen downward trends in fossil CO_2 emissions, particularly over the last decade. Among the rest of the OECD countries, Colombia, Costa Rica, Korea, and Turkey, have all seen clear upward trends.

For the dependent variable in our analysis, we use relative emission intensity as a function of GDP rather than absolute emissions. This is common practice in empirical literature including Eskander & Fankhauser (2020) and Agnolucci & Arvanitopoulos (2019) as it controls for the size of different countries and their levels of economic activity. After controlling for GDP, almost all countries in our sample experience declining trends in emission intensity over the last two decades.

2.6. Fossil CO_2 emissions by sector

We also disaggregate fossil CO_2 emissions by sector using the same sectoral classification outlined in the previous section for policy density. Figure 4 shows that sectoral CO_2 emission shares vary widely between countries and over time reflecting distinct economic and market characteristics.

The two energy supply sectors are electricity and heat production, and energy industry own use. Figure 4 shows that the electricity and heat production sector (including relevant industrial subsectors) has been responsible for the largest share of fossil CO_2 emissions in most countries, with exceptions mainly being smaller economies such as Costa Rica, Switzerland, Luxembourg, and Iceland, or larger economies like France and Norway that have high shares of low-carbon power generation technologies such as nuclear and renewables. The energy industry own use sector includes all emissions generated by energy transformation processes (e.g., extraction, refining, biofuel production, hydrogen production) other than those used in the generation and supply of electricity and heat. Countries with large energy resource endowments such as Norway, Russia, Canada, Mexico, and Chile have higher shares of emissions from this sector.

The three energy demand sectors are manufacturing and construction, buildings, and transport. The manufacturing and construction sector includes all emissions from industrial processes and energy intensive industries such as iron and steel, non-ferrous metals, and chemicals. As the IEA reports CO_2 emissions associated with the steel industry under the iron and steel classification and not as part of the energy industry own use, emissions produced using coke in blast furnaces are reported as industrial emissions. Figure 4 shows that four BRIICS economies - China, India, Brazil, Indonesia - have a high share of emissions generated from this sector. In the OECD, countries with significant high emission industrial activity include Belgium, Colombia, France, Japan, Korea, and Turkey. The buildings sector includes emissions from residential and commercial buildings and includes the services sector in the IEA classifications. Figure 4 shows that OECD countries with higher economic activity in the services sector such as Belgium, France, Ireland, Switzerland, and the UK, have higher shares of emissions from this sector. The transport sector incorporates fossil CO_2 emissions generated from economic activities involving rail and road transport, and aviation. Most countries in our sample (both OECD and BRIICS) have a large share of emissions from transport.

Fossil CO_2 emissions from the agricultural sector are a very small share of total emissions (with Iceland as the only exception) and are excluded from our analysis.

Figure 4. Sectoral shares of fossil CO_2 emissions, with countries split between upper and lower panel to aid visualisation.

2.7. Economic, political, and geographic control variables

We follow Eskander & Fankhauser (2020)'s inclusion of a range of control variables to account for other political, economic, and geographic determinants of emissions intensity. This accounts for any underlying variation in our covariates that is not related to our independent variables for capturing the effectiveness of climate policies.

For political controls, we use the rule of law index, estimated by the World Bank on an annual basis for all countries globally, and interpreted as a proxy for policy implementation capacity. Countries with strong rule of law are expected to be effective in the implementation of climate policies, in contrast to countries with weak rule of law. As our country sample covers only OECD and BRIICS economies, we expect rule of law to be less significant as a control variable than in the Eskander & Fankhauser (2020) study which included a long tail of less developed economies with lower policy implementation capacity.

For economic controls, we use the log of GDP per capita and its interaction with the square term to control for the existence of an inverted U-shaped relationship between emissions intensity and GDP per capita (e.g., Agnolucci & Arvanitopoulos (2019)). This is known as the Kuznets curve, and controls for the development stage of the country and its effect on emissions (Stern, 2004). We also include the share of total economic activity in the services sector for each country to control for the structural shift from manufacturing and industrial activities to services. Countries with larger industrial sectors tend to be more emissions intensive than those with larger services sector. Additionally, we control for a country's import dependence by including the share of imports compared to the overall level of economic activity within a country. We expect that a higher import share would indicate more services-oriented developed countries that import emission-intensive products from other countries with increased economic activity in their industrial sector. This phenomenon is also known in the literature as carbon leakage (Arvanitopoulos et al., 2021). Finally, the Hordick-Prescott GDP filter controls for cyclical volatility in economic activity. Although there is some empirical evidence suggesting that emissions tend to be more cyclically volatile that economic output (Doda, 2014), we do not form any strong expectation for this control.

For geographic controls, we incorporate the annual temperature variation from the long-term average to control for the effect of climatic conditions on emissions intensity. We expect an increase in air temperature above the long-term average to be associated with lower emission intensities, particularly for countries in the Northern hemisphere with winter heating seasons.

This set of control variables is identical to those used by Eskander & Fankhauser (2020), but applied in this study to our OECD + BRIICS country sample over the timer period 2000-2018.

3. Method

Our overall method has four main steps designed to test the historical relationships between climate policies and emission intensities, beginning first with a replication of the Eskander & Fankhauser (2020) study, and moving sequentially through layers of additional testing and complexity with the policy variables unique to this study.

3.1. Regression model replication of Eskander & Fankhauser (2020)

We first perform a validation test of our regression model by replicating Eskander & Fankhauser (2020)'s model specification on our data. We have a smaller country sample (44 OECD + BRIICS countries vs. 133 countries) but a larger policy dataset (n=2,909 IEA PMD policies vs. n=1,000 CCLW legislations) over a similar length time period (2000-2018 vs.

1996-2016). Despite these differences, we expect to confirm the main empirical findings of Eskander & Fankhauser (2020) on the long-term effect of climate policies on emission intensity. Equation 1 represents the regression model specified in Eskander & Fankhauser (2020):

$$\ln\left(\frac{CO2}{GDP}\right)_{it} = \alpha + \beta_1 Pdens_{it}^{S} + \beta_2 Pdens_{it}^{L} + \beta_3 X_{it} + \theta_\iota + \eta_\tau + \varepsilon_{it}, \qquad (1)$$

where $\ln\left(\frac{CO2}{GDP}\right)_{it}$ stands for the log of emissions intensity per country *i* and year *t*; α is the constant parameter; $Pdens_{it}^{S}$ is the short-term policy density measured by the number of legislations per country *i* for years *t*, *t-1*, and *t-3*; $Pdens_{it}^{L}$ is the long-term policy density measured by the cumulative number of climate policies per country *i* for year *t*; X_{it} stands for all controls; θ_ι are country fixed effects; η_τ are year fixed effects; and ε_{it} are the residuals that are independent and identically distributed (i.i.d.). Following Eskander & Fankhauser (2020) we introduce a 1-year lag operator to both independent variables and all controls.

3.2. Baseline regression model

Having replicated the model specification of Eskander & Fankhauser (2020), we move on to our baseline model that is better suited to our more comprehensive policy dataset that includes both past and existing climate polices (in contrast to CCLW that omits repealed climate laws). Consequently, we do not incorporate a short-term policy density variable which was used by Eskander & Fankhauser (2020) as a proxy for unobserved (omitted) past climate policies. Our baseline model has the further advantage of being easy to augment with additional variables capturing specialisation in policy instrument types and sectoral policies within a country. Equation 2 represents our full baseline regression model:

$$\ln\left(\frac{CO2}{GDP}\right)_{it} = \alpha + \beta_1 Pdens_{it} + \beta_2 X_{it} + \theta_\iota + \eta_\tau + \varepsilon_{it}, \qquad (2)$$

where $\ln\left(\frac{CO2}{GDP}\right)_{it}$ stands for the natural log of emissions intensity per country *i* and year *t*; α is the constant parameter; $Pdens_{it}$ is the total policy density measuring the cumulative number of climate policies per country *i* for year *t*; X_{it} stands for all controls; θ_ι are the country fixed effects; η_τ are year fixed effects; and ε_{it} are the residuals that are independent and identically distributed (i.i.d.).

We can check the robustness of our proposed methodological approach by observing whether the coefficients of independent variables and controls change in sign, magnitude, or significance relative to the replication model of Eskander & Fankhauser (2020). We expect the two models in equations 1 and 2 to be very similar. In particular, we expect policy density to be negative and significant as an indication of climate policy effectiveness for reducing emission intensities after controlling for the level of economic activity in each country.

3.3. Augmented baseline model

Next, we control for the effect of policy instrument specialisation and sectoral policy specialisation on historical emission intensities. To do that, we incorporate in our baseline regression model (equation 2) the HHI measuring the level of specialisation among policy instrument types or sectoral policy coverage. Equation 3 represents our augmented regression model:

$$\ln\left(\frac{CO2}{GDP}\right)_{it} = \alpha + \beta_1 Pdens_{it} + \beta_2 HHI_{it} + \beta_3 X_{it} + \theta_\iota + \eta_\tau + \varepsilon_{it}, \qquad (3)$$

where $\ln(\frac{CO2}{GDP})_{it}$ is the natural log of emissions intensity per country *i* and year *t*; α is the constant parameter; $Pdens_{it}$ is the total policy density measuring the cumulative the number of climate policies per country *i* for year *t*; HHI_{it} stands for the Herfindahl-Hirschman Index per country *i* for year *t;* X_{it} stands for all controls; θ_ι are the country fixed effects; η_τ are year fixed effects; and ε_{it} are the residuals that are independent and identically distributed (i.i.d.).

We constructed four different HHI variables, two controlling for policy instrument types (with 8 and 3 categories respectively) and the other two controlling for sectoral policies (emissions-weighted and non-weighted respectively). As a result, we estimate four separate regression models, each with one of the four HHI variables.

3.4. Energy demand sector models

Finally, we investigate the effectiveness of climate policies targeting energy demand for reducing sectoral emission intensities. We use our baseline regression model specified in equation 2 and perform independent regression analysis for each sector separately including industry, buildings, and transport (as well as the two energy supply sectors). We disaggregate both fossil CO_2 emissions and climate policies to their corresponding sectors.

For the dependent variable, we divide sectoral fossil CO_2 emissions by national GDP to control for the size of the economy. This is a workaround as the sectoral classifications for economic activity do not match the equivalent sectoral classification used by IEA for emissions. For the independent variable, we calculate sectoral policy density as the cumulative total of all past and existing climate policies in each sector. Controls remain the same across all sectoral regression models.

We expect sectoral policy density to be negative and statistically significant indicating the effectiveness of sectoral policies in reducing historical emission intensities after controlling for the level of economic activity within the country.

4. Results

4.1. Replicating Eskander & Fankhauser (2020)'s findings on policy density

Overall, our results are very similar to those estimated in Eskander & Fankhauser (2020) as expected, despite our smaller country sample, much larger policy dataset, and slightly later 18 year time period. The coefficients for both the short-term and long-term policy density variables are negative, confirming our expectation that a higher stock of climate policies within a country is associated with larger emission reductions when controlling for the size of the economy. However, in Eskander & Fankhauser (2020), both coefficients for short-term and long-term policy density are negative and statistically significant (column 2 in Table 1) whereas in our replication model short-term policy density is not statistically significant (column 1 in Table 1). This can be attributed to differences in the underlying policy datasets. Eskander & Fankhauser (2020) introduce the short-term policy density variable in their baseline model to control for the omission from the CCLW dataset of climate laws that have been repealed which means their effect is not captured by the long-term policy density variable. The IEA PMD used in our study does not have this limitation as it captures all past and existing climate policies since 2000. We reason that our coefficient for long-term policy density effectively captures the effect of all climate polices, which explains why the coefficient for short-term policy density is statistically non-significant as there is no variation left to capture.

Our coefficients for short-term and long-term policy density variables in Table 1 are smaller in absolute size than those estimated in Eskander & Fankhauser (2020). This difference can be attributed to the different sample of countries used in the two studies. We focus on 44 OECD and BRIICS countries, while Eskander & Fankhauser (2020) employ a global dataset of 133 countries.

This also explains why the coefficient for the rule of law index is not statistically significant in our study. Given we focus mainly on advanced economies with homogenous institutional characteristics, the effective implementation of legislation is being captured by the policy density variable. In contrast, Eskander & Fankhauser (2020) include large numbers of developing countries in their sample thar are characterised by comparatively weaker rule of law. Thus, this variation between developed and developing countries is being picked up by the coefficient for the rule of law index which becomes statistically significant in their model.

The coefficient for the log of GDP per capita is positive and statistically significant while its interaction with the square term is negative and statistically significant. This confirms findings in Eskander & Fankhauser (2020) on the existence of U-shaped relationship between emissions intensity and GDP per capita (Stern, 2004).

We also confirm the expectation that advanced economies are net importers of energy-intensive goods which reduces their emissions while increasing those of exporting countries. This carbon leakage effect seen in the negative and statistically significant coefficient for the share of imports to GDP (Arvanitopoulos et al., 2021). This finding is similar to the sensitivity test of Eskander & Fankhauser (2020) using only EU and non-EU OECD countries instead of their full 133 country sample (column 3 in Table 1).

Finally, we find the coefficient for the share of services to GDP and for temperature variation from the long-term average to be negative, similar to Eskander & Fankhauser (2020), but statistically non-significant.

Table 1. Replication of the baseline regression model in Eskander & Fankhauser (2020).

Variables	Log (CO_2/GDP) (1)	Log (CO_2/GDP) - Eskander and Fankhauser (2020) (2) Full sample (133 countries)	Log (CO_2/GDP) - Eskander and Fankhauser (2020) (3) EU and non-EU OECD countries only
(L1) Policy density last 3 years	-0.00074	Negative***	Negative**
	(0.00055)		
(L1) Total policy density	-0.000634***	Negative***	Negative***
	(0.000238)		
(L1) Rule of law	0.0126	Negative***	Negative
	(0.0329)		
(L1) Hodrick-Prescott GDP filter	-0.138	Positive*	Negative
	(0.216)		
(L1) GDP per cap log	2.382***	Positive***	Negative
	(0.357)		
(L1) GDP per cap interaction with square term	-0.128***	Negative***	Negative
	(0.0196)		
(L1) Imports share to GDP	-0.0042***	Positive***	Negative*
	(0.0006)		
(L1) Services share to GDP	-0.0022	Negative**	Negative**
	(0.0022)		
(L1) Temperature variation	-8.70e-05	Negative*	Negative*
	(0.0066)		
Constant	-12.15***		
	(1.632)		
Observations	704		
R-squared	0.978		
Within R-squared	0.157		
RMSE	0.075		

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Columns 2 and 3 show the sign and statistical significance for the equivalent coefficients in the corresponding regression models in Eskander and Fankhauser (2020).

4.2. Baseline regression model to test effectiveness of policy density

Having estimated our replication model of Eskander & Fankhauser (2020) and confirmed its basic insight on the significant negative effect of policy density on emission intensity, we now present our full baseline model which does not require a lag structure in the independent variable(s) or the controls. Our policy density variable is a cumulative measure of all past policies and thus it controls for the effect of all past and existing climate policies. Consequently, we expect no major differences between the replication model (Table 1) and our full baseline model (model 1 in Table 2), and indeed, they are remarkably similar.

The coefficients in our full baseline model for policy density, GDP per capita and its interaction with the square term, and share of imports to GDP, remain statistically significant and have comparable magnitude to those in the replication model. None of the coefficients in our full baseline model change in sign. Minor differences only can be observed in the coefficient for the temperature variation from the long-term average that increases in magnitude (in absolute terms) while becoming weakly statistically significant.

As a robustness test, we test a second baseline model (model 1 in Table 2) by replacing the policy density variable with a 3-year lagged version. We expect the coefficient of the lagged policy density variable to be very similar to the contemporaneous one, given our cumulative total policy density variable accounts for all past and existing climate policies. This is indeed the case, with the coefficient of the 3-year lagged policy density variable being slightly larger in absolute terms. One interpretation is that the full effect of climate policy on emission intensity is felt just a few years after policies are legislated. This result indicates strong path dependence on climate policy implementation and their consequent effect on emission intensity reduction.

Coefficients for the controls are also very similar between the two baseline model specifications (model 1 vs. model 2 in Table 2). Minor exceptions involve the coefficient for Hodrick-Prescott GDP filter that becomes weakly statistically significant in model 2 (lagged policy density) compared to model 1 (contemporaneous policy density), and the coefficient for the temperature variation from the long-term average that increases in magnitude and become statistically significant in model 2 compared to weakly statistically significant in model 1.

Overall, the similarities between models 1 and 2 in Table 2 demonstrate that our policy density variable effectively accounts for the long-term effect of the stock of all past and existing climate policies on emissions intensity reduction.

Table 2. Our full baseline regression model, with two different specifications: model 1 with contemporaneous policy density, and model 2 with lagged policy density.

Variables	Log (CO_2/GDP) (1)	Log (CO_2/GDP) (2)
Total policy density	-0.000536***	
	(0.000190)	
Total policy density - Lag 3 years		-0.000632***
		(0.000230)
Rule of law	-0.0142	0.000661
	(0.0300)	(0.0334)
Hodrick-Prescott GDP filter	-0.366	-0.458*
	(0.229)	(0.236)
GDP per cap log	2.643***	2.441***
	(0.294)	(0.376)
GDP per cap interaction with square term	-0.145***	-0.132***
	(0.0166)	(0.0206)
Imports share to GDP	-0.00340***	-0.00306***
	(0.000670)	(0.000663)
Services share to GDP	-0.000629	-0.000784
	(0.00213)	(0.00233)
Temperature variation	-0.0108*	-0.0169***
	(0.00644)	(0.00635)
Constant	-13.08***	-12.44***
	(1.276)	(1.714)
Observations	791	703
R-squared	0.977	0.978
Within R-squared	0.193	0.1652
RMSE	0.078	0.0743

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

4.3. Augmented regression models to test effect of instrument types and sectoral coverage

Our results so far support the robustness of our baseline model and the effectiveness of policy density for reducing emissions intensity. Using the more detailed information available in the IEA PMD, we are now able to use our augmented models to test the effect of policy instrument types and sectoral policy coverage. This gives us more granular insights on climate policy design effectiveness.

Models 1 and 2 in Table 3 present the baseline regression model augmented with additional variables for the HHIs for 8 and 3 policy instrument types respectively. Coefficients for these HHI variables are negative, statistically significant, and have comparable magnitudes. A higher specialisation in particular policy instrument types (higher HHI) is associated with larger reductions in emission intensity. As the coefficient for the more aggregated HHI based on 3 instrument types is slightly smaller, the relative importance of higher specialisation for reducing emissions intensity decreases at a higher level of instrument aggregation. The effect of both policy density and the controls remains virtually identical in both models, and also with the baseline regression model 1 in Table 2. This further support the robustness of the baseline model.

Models 3 and 4 in Table 3 present the baseline regression model augmented with an additional variable for the HHI for sectoral policies weighted by the sectoral share of emissions, and for the HHI for non-weighted sectoral policies respectively. Similar to the HHI for policy instrument types, results show that higher policy specialisation in particular sectors is associated with larger reductions in emission intensity. The coefficient for the weighted sectoral HHI (model 3) is almost twice as large as that for the unweighted sectoral HHI (model 4). As expected, policy specialisation in emission-intensive sectors is associated with larger reductions in emission intensity. The coefficient for policy density variable reduces more alongside the unweighted sectoral HHI (model 4) than for the weighted sectoral HHI (model 3). But it remains broadly consistent with other results shown in Table 3, as well as in the baseline model shown in Table 2. The controls also have very similar effects across the different model specifications (with minor differences in the Hodrick-Prescott GDP filter and the temperature variation from the long-term average).

Overall, augmented model results in Table 3 show that higher specialisation in policy instrument types is strongly associated historically with larger emission reductions after controlling for the size of the economy. And similarly, higher policy specialisation in emission-intensive sectors is also strongly associated with falling emission intensity, particularly over the long-term.

To further examine the effect of policy specialisation in particular sectors, and particularly the energy demand sectors of buildings, industry, and transport, the final step of our methodology uses sectoral fossil CO_2 emissions in the construction of our dependent variable.

Table 3. Augmented regression models

Variables	Log (CO_2/GDP) (1)	Log (CO_2/GDP) (2)	Log (CO_2/GDP) (3)	Log (CO_2/GDP) (4)
Total policy density	-0.000542***	-0.000569***	-0.000531***	-0.000457**
	(0.000190)	(0.000189)	(0.000192)	(0.000191)
HHI - 8 instruments	-0.0886***			
	(0.0338)			
HHI - 3 instruments		-0.0764**		
		(0.0365)		
HHI sectoral - emissions weighted			-0.148**	
			(0.0752)	
HHI sectoral – non-weighted				-0.0996**
				(0.0440)
Rule of law index	-0.0229	-0.0230	-0.0193	-0.0260
	(0.0307)	(0.0311)	(0.0312)	(0.0306)
Hodrick-Prescott GDP filter	-0.444*	-0.463**	-0.439*	-0.393*
	(0.229)	(0.229)	(0.224)	(0.224)
GDP per cap log	2.577***	2.594***	2.641***	2.648***
	(0.318)	(0.322)	(0.325)	(0.318)
GDP per cap interaction with square term	-0.141***	-0.141***	-0.143***	-0.144***
	(0.0178)	(0.0180)	(0.0183)	(0.0178)
Imports share to GDP	-0.00265***	-0.00265***	-0.00250***	-0.00256***
	(0.000651)	(0.000652)	(0.000662)	(0.000644)
Services share to GDP	-0.00133	-0.00135	-0.00145	-0.00123
	(0.00215)	(0.00218)	(0.00222)	(0.00214)
Temperature variation	-0.0160**	-0.0158**	-0.0147**	-0.0136**
	(0.00636)	(0.00638)	(0.00634)	(0.00630)
Constant	-12.83***	-12.92***	-13.21***	-13.17***
	(1.403)	(1.414)	(1.430)	(1.396)
Observations	763	763	767	767
R-squared	0.978	0.978	0.978	0.978
Within R-squared	0.18	0.177	0.170	0.175
RMSE	0.075	0.075	0.075	0.075

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

4.4. Sectoral models to test effectiveness of policy density in buildings, transport and industry

Our granular dataset of policies matched to specific energy demand and supply sectors allows us to test the effectiveness of policy density within each sector for reducing emission intensities. We disaggregate both fossil CO_2 emissions (dependent variable) and policies (independent variables) by sector, in order to re-estimate the baseline regression model for each sector independently.

By disaggregating policy density by sector, we reduce the variation within the covariates of the regression model as specific sectors have very small numbers of policies. This creates issues for smaller economies such as Costa Rica (no policies in the industry sector) and Iceland (no policies in the industry sector, and only one policy in the buildings sector). In addition, Iceland generates virtually no emissions from its energy supply based on geothermal energy. Consequently, we remove Iceland and Costa Rica from this part of our analysis. We also adjust our fixed effects in response to the smaller variation among our covariates in our sectoral models. Instead of using separate dummies for each year and country, we use a consistent linear or ‘continuous’ time trend for each country. In this way, we effectively control for heterogenous (different countries) slopes (continuous time trend effect within each country). These adjustments do not affect our ability to interpret results in similar ways as for earlier baseline and augmented models.

We present the results for the energy demand sectors in Table 4. Coefficients for both the contemporaneous and the 3-year lagged policy density variables are negative across all models. The coefficients for policy density are statistically significant for the industry (manufacturing and construction) and transport sectors, but not for the buildings sector. These coefficients for policy density in the industry and transport sectoral models are also much higher than the coefficient in the baseline regression model (model 1 in Table 2). This implies that in these two energy demand sectors, cumulative total climate policies are more effective in reducing emission intensity.

The lack of statistical significance for the policy density variable in the buildings sector is against expectations. Our best interpretation is that emission reductions from building sector activity such as reduced electricity consumption (due to efficiency measures) are picked up in the upstream electricity and heat production sector. In contrast, industry activity and particularly transport activity involves direct combustion of fossil fuels so CO_2 emissions are directly accounted for downstream in the demand sectors. However, the lack of statistical significance for policy density in the buildings sectors may also be a statistical artefact of low policy densities within certain countries. These interpretations warrant further investigation.

Of the controls, GDP per capita is consistently positive and statistically significant across all sectoral models (Table 4), and its interaction with the square term is negative and significant as expected. For the other controls, there is a larger variation in coefficients across the sectoral models in terms of sign, statistical significance, or magnitude. We attribute this to the lower variation in the covariates (for the reasons discussed earlier) which allows the controls to capture the effect on emissions intensity that is not being captured by sectoral emissions intensity. The coefficient for rule of law index is statistically significant for the transport sector, possibly indicating that countries with lower number of policies for the transport sector are those with weaker rule of law. The coefficient for the Hodrick-Prescott GDP filter is positive and statistically significant for the industry sector, suggesting that industry emissions are more cyclically volatile than overall economic output. The coefficient for the share of imports to GDP is negative and statistically significant for the industry and transport sectors. This is reasonable as these two sectors are more likely to be negatively affected if imports on emission intensive products are increased. The coefficient for the share of services to GDP is also negative and statistically significant for industry and transport sectors. Our interpretation is that countries with larger service sectors tend to have lower levels of economic activity in energy-intensive industry and so lower emissions intensity. Finally, the coefficient for temperature variation from the long-term average is statistically significant only for the building sector. Higher temperatures than the long-term average reduce energy consumption for heating in many Northern hemisphere countries, so reducing sectoral emission intensity.

Table 4. Baseline models for energy demand sectors

	Buildings Log (CO_2/GDP)		Industry Log (CO_2/GDP)		Transport Log (CO_2/GDP)	
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Total policy density (sectoral)	-0.0006		-0.006***		-0.0055***	
	(0.0007)		(0.0018)		(0.0005)	
Total policy density (sectoral) - Lag 3 years		-0.0005		-0.007***		-0.0054***
		(0.0009)		(0.00232)		(0.0006)
Rule of law index	-0.0493	-0.0239	0.00185	-0.0109	-0.0922***	-0.0693**
	(0.0632)	(0.0714)	(0.0540)	(0.0593)	(0.0291)	(0.0313)
Hodrick-Prescott GDP filter	-0.205	-0.249	1.145***	1.089***	-0.00233	0.0141
	(0.382)	(0.342)	(0.344)	(0.362)	(0.183)	(0.181)
GDP per cap log	4.621***	5.366***	5.009***	4.158***	1.722***	2.124***
	(0.697)	(0.922)	(0.529)	(0.757)	(0.261)	(0.342)
GDP per cap interaction with square term	-0.269***	-0.306***	-0.276***	-0.233***	-0.0868***	-0.108***
	(0.0365)	(0.0473)	(0.0281)	(0.0393)	(0.0139)	(0.0176)
Imports share to GDP	-0.0012	0.0002	-0.006***	-0.007***	-0.0026***	-0.0037***
	(0.0016)	(0.0017)	(0.0015)	(0.0018)	(0.0007)	(0.0006)
Services share to GDP	-0.0193***	-0.0189***	-0.019***	-0.021***	-0.00100	-0.00193
	(0.004)	(0.004)	(0.0033)	(0.0036)	(0.0021)	(0.0021)
Temperature variation	-0.0653***	-0.0729***	0.0133	0.00952	-0.0055	0.00660
	(0.0139)	(0.0126)	(0.0118)	(0.0119)	(0.00547)	(0.0056)
Observations	753	669	755	671	755	671
R-squared	0.998	0.998	0.998	0.998	0.999	1.000
Within R-squared	0.520	0.506	0.528	0.438	0.488	0.498
RMSE	0.177	0.165	0.164	0.163	0.071	0.067

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

As a final set of models, we repeat the sectoral analysis of the two upstream sectors: electricity and heat production, and energy industry own use (Table 5). The coefficient for policy density for the electricity and heat production sector is negative and statistically significant both for the contemporaneous and the lagged effect (models 1 and 2). The coefficient for policy density in the energy industry own use sector is negative but statistically non-significant for the contemporaneous effect but negative and statistically significant for the lagged effect (models 3 and 4). This could indicate that climate polices take longer to have an effect on emitting activity in the energy extraction and processing industries with their long capital investment horizons.

From the controls, we observe that the coefficient for GDP per capita is consistently positive and statistically significant for all models, while its interaction with the square term is negative and significant (Table 5). The coefficient for Hodrick-Prescott GDP filter is positive and statistically significant only for the energy industry own use sector (models 3 and 4) indicating that emissions from this sector are more cyclically volatile than economic output. The coefficient for rule of law index is statistically significant for the energy industry own use sector (models 3 and 4), possibly indicating that countries with fewer sectoral policies are those with weaker rule of law. The coefficient for the share of imports to GDP is negative and statistically significant for all models in Table 5. This is reasonable as an increase in imports of energy intensive products would reduce energy consumption in energy demand sectors with knock-on effects on upstream activity in the energy supply sector. The coefficient for the share of services to GDP is positive and statistically significant in the energy industry own use sector (models 3 and 4). This result is hard to interpret. The coefficient for the temperature variation from the long-term average is statistically significant for the electricity and heat production sector (models 1 and 2), indicating that higher than average temperature in northern latitudes reduce demand for electricity.

Table 5. Baseline models for energy supply sectors

	Electricity and heat production Log (CO_2/GDP)		**Energy industry own use Log (CO_2/GDP)**	
Variables	**(1)**	**(2)**	**(3)**	**(4)**
Total policy density (sectoral)	-0.00406***		-0.00195	
	(0.0012)		(0.0013)	
Total policy density (sectoral) - Lag 3 years		-0.0055***		-0.00290**
		(0.0015)		(0.0012)
Rule of law index	0.0200	0.0529	-0.420***	-0.399***
	(0.070)	(0.080)	(0.062)	(0.054)
Hodrick-Prescott GDP filter	0.415	0.534	0.730**	0.747**
	(0.462)	(0.487)	(0.332)	(0.307)
GDP per cap log	4.855***	5.615***	2.670***	2.857***
	(0.545)	(0.757)	(0.392)	(0.438)
GDP per cap interaction with square term	-0.259***	-0.297***	-0.156***	-0.163***
	(0.0300)	(0.0403)	(0.0216)	(0.0234)
Imports share to GDP	-0.0107***	-0.0107***	-0.00372**	-0.00398***
	(0.00287)	(0.00276)	(0.00152)	(0.00128)
Services share to GDP	-0.00350	-0.00488	0.0130***	0.0111***
	(0.006)	(0.0064)	(0.0035)	(0.0033)
Temperature variation	-0.0931***	-0.0866***	-0.00972	-0.0174
	(0.0213)	(0.0213)	(0.0139)	(0.0112)
Observations	755	671	755	671
R-squared	0.995	0.995	0.999	0.999
Within R-squared	0.408	0.429	0.357	0.365
RMSE	0.229	0.219	0.161	0.138

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

5. Discussion

We know from Eskander & Fankhauser (2020) that higher policy density (cumulative total numbers of policies) is strongly associated with reductions in emission intensity (CO_2/GDP) as a generalisable effect across 133 countries. In our analysis, we confirm this finding holds for 44 OECD+BRIICS countries that account for 80.6% of total global fossil CO_2 emissions, particularly as a contemporaneous (immediate) effect.

By coding policies by instrument type and by sectoral activity, we extend this analysis to look at the relative benefits of diversity or balance vs. specialisation or concentration in both policy instrument choices and sectoral coverage. We find evidence that higher specialisation within policy instrument types is strongly associated with larger reductions in emission intensity. However, this analysis does not reveal whether specific instrument types consistently outperform others in reducing emission intensity. Countries may follow paths tailored to their own governance traditions and market contexts, selecting particular instrument types proven to work well locally. Tentative support for this interpretation is seen in Figure 2 which plots the distribution over time of policy instrument types within each country. Regulatory and market-based instruments are the most widely adopted policy instrument type adopted, but the relative shares of each differs substantially both among countries and over time. Countries like Mexico and Turkey implement mainly regulatory policies, whereas countries like Estonia and Finland implement mainly market-based policies.

We similarly show that that higher specialisation within sectoral policies is strongly associated with larger reductions in emission intensity, particularly when specialisation is weighted towards high emitting sectors. However, this analysis too does not reveal whether policies should be concentrated in specific sectors in order to have the greatest effect on emission intensity. Figure 3 shows that sectoral policies are not uniformly distributed across countries and over time. For example, countries like Chile have implemented climate policies mainly for the energy supply sectors, whereas Switzerland and Slovenia have a larger share of policies focusing on the transport sector.

Although specialisation is effective in reducing emission intensity, there is no single policy instrument type nor sectoral policy that is more effective than the rest.

Focusing on the three main energy demand sectors – buildings, industry, and transport - we show that sectoral policy density within each is an important driver of emission intensity reductions. In particular, our model coefficients for policy density are large in magnitude for industry and transport, indicating the effectiveness of climate policy in these demand sectors.

Finally, we note certain limitations in our analysis, particularly with respect to data availability on policy instrument types and sectoral disaggregation before 2000. Similarly, economic, political, and geographic variables used as controls in our analysis are based on available data resources for countries and sectoral aggregations. Future studies with different set of countries and/or sectors would have to draw on more disaggregated sectoral data sources to examine the robustness of the sectoral findings in this study.

We have also not examined the effect of the wider policy landscape in terms of climate governance institutions. Future work should account for the presence or absence of net-zero targets (or other long-term emission reduction targets), the presence of dedicated climate ministries, independent advisory boards on climate change mitigation, and alternative governance regimes.

References

Agnolucci, P., & Arvanitopoulos, T. (2019). Industrial characteristics and air emissions: Long-term determinants in the UK manufacturing sector. *Energy Economics*, *78*. https://doi.org/10.1016/j.eneco.2018.12.005

Arvanitopoulos, T., Garsous, G., & Agnolucci, P. (2021). Carbon leakage and agriculture: A literature review on emissions mitigation policies. *OECD Food, Agriculture and Fisheries Papers, No. 169, OECD Publiishing Paris*. https://doi.org/10.1787/9247f1e7-en.

Carley, S., & Miller, C. J. (2012). Regulatory Stringency and Policy Drivers: A Reassessment of Renewable Portfolio Standards. *Policy Studies Journal*, *40*(4), 730–756. https://doi.org/10.1111/j.1541-0072.2012.00471.x

del Rio, P., & Howlett, M. P. (2013). Beyond the “Tinbergen Rule” in Policy Design: Matching Tools and Goals in Policy Portfolios. *Lee Kuan Yew School of Public Policy Research Paper No. 13-01*. https://doi.org/10.2139/ssrn.2247238

Doda, B. (2014). Evidence on business cycles and CO2 emissions. *Journal of Macroeconomics*, *40*. https://doi.org/10.1016/j.jmacro.2014.01.003

Dudley, H., Jordan, A. J., & Lorenzoni, I. (2021). ScienceBrief Review: Independent expert advisory bodies facilitate ambitious climate policy responses. In *Critical Issues in Climate Change Science, edited by: Corinne Le Quéré, Peter Liss & Piers Forster*. https://doi.org/10.5281/ZENODO.4633677

Eskander, S. M. S. U., & Fankhauser, S. (2020). Reduction in greenhouse gas emissions from national climate legislation. *Nature Climate Change*, *10*(8), 750–756. https://doi.org/10.1038/s41558-020-0831-z

GCP. (2021). *Global Carbon Budget 2021, Global Carbon Project (GCP)*.

Ginevičius, R., & Čirba, S. (2007). Determining market concentration. *Journal of Business Economics and Management*, *8*(1). https://doi.org/10.1080/16111699.2007.9636147

Grubb, M., Drummond, P., Poncia, A., McDowall, W., Popp, D., Samadi, S., Penasco, C., Gillingham, K. T., Smulders, S., Glachant, M., Hassall, G., Mizuno, E., Rubin, E. S., Dechezleprêtre, A., & Pavan, G. (2021). Induced innovation in energy technologies and systems: A review of evidence and potential implications for CO2 mitigation. *Environmental Research Letters*, *16*(4). https://doi.org/10.1088/1748-9326/abde07

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., Rao, N. D., Riahi, K., Rogelj, J., De Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., … Valin, H. (2018). A low energy demand scenario for meeting the 1.5 °c target and sustainable development goals without negative emission technologies. *Nature Energy*, *3*(6). https://doi.org/10.1038/s41560-018-0172-6

Hale, T., Kuramochi, T., Lang, J., Mapes, B., Smith, S., Aiyer, R., Black, R., Boot, M., Chalkley, P., Hans, F., Hay, N., Hsu, A., Höhne, N., Mooldijk, S., & Walsh, T. (2021). *Net Zero Tracker*. Energy and Climate Intelligence Unit, Data-Driven EnviroLab, New Climate Institute, Oxford Net Zero.

IEA. (2018). CO2 emissions from fuel combustion 2018 overview. *OECD/IEA, Paris*.

Kivimaa, P., & Kern, F. (2016). Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. *Research Policy*, *45*(1). https://doi.org/10.1016/j.respol.2015.09.008

Knill, C., Schulze, K., & Tosun, J. (2012). Regulatory policy outputs and impacts: Exploring a complex relationship. *Regulation and Governance*, *6*(4). https://doi.org/10.1111/j.1748-5991.2012.01150.x

Knudson, W. A. (2009). The Environment, Energy, and the Tinbergen Rule. *Bulletin of Science, Technology & Society*, *29*(4). https://doi.org/10.1177/0270467608325375

Le Quéré, C., Jackson, R. B., Jones, M. W., Smith, A. J. P., Abernethy, S., Andrew, R. M., De-Gol, A. J., Willis, D. R., Shan, Y., Canadell, J. G., Friedlingstein, P., Creutzig, F., & Peters, G. P. (2020). Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. *Nature Climate Change*, *10*(7). https://doi.org/10.1038/s41558-020-0797-x

Lockwood, M. (2013). The political sustainability of climate policy: The case of the UK Climate Change Act. *Global Environmental Change*, *23*(5). https://doi.org/10.1016/j.gloenvcha.2013.07.001

Mundaca, L., Ürge-Vorsatz, D., & Wilson, C. (2019). Demand-side approaches for limiting global warming to 1.5 °C. In *Energy Efficiency* (Vol. 12, Issue 2). https://doi.org/10.1007/s12053-018-9722-9

OECD. (2010). The Innovation Policy Mix. In *OECD Science, Technology and Industry Outlook 2010, OECD Publishing, Paris*. https://doi.org/10.1787/sti_outlook-2010-48-en.

OECD. (2015). System Innovation: Synthesis Report. In *OECD Publishing, Paris*.

Pahle, M., Burtraw, D., Flachsland, C., Kelsey, N., Biber, E., Meckling, J., Edenhofer, O., & Zysman, J. (2018). Sequencing to ratchet up climate policy stringency. *Nature Climate Change*, *8*(10), 861–867. https://doi.org/10.1038/s41558-018-0287-6

Russo, M., & Pavone, P. (2021). Evidence-based portfolios of innovation policy mixes: A cross-country analysis. *Technological Forecasting and Social Change*, *168*. https://doi.org/10.1016/j.techfore.2021.120708

Schaffer, L. M., Oehl, B., & Bernauer, T. (2021). Are policymakers responsive to public demand in climate politics? *Journal of Public Policy*. https://doi.org/10.1017/S0143814X21000088

Schaub, S., Tosun, J., Jordan, A. J., & Enguer, J. (2022). *Climate Policy Ambition: A Policy-Density Perspective*.

Schmidt, T. S., & Sewerin, S. (2019). Measuring the temporal dynamics of policy mixes – An empirical analysis of renewable energy policy mixes' balance and design features in nine countries. *Research Policy*, *48*(10). https://doi.org/10.1016/j.respol.2018.03.012

Stern, D. I. (2004). The Rise and Fall of the Environmental Kuznets Curve. *World Development*, *32*(8). https://doi.org/10.1016/j.worlddev.2004.03.004

Sterner, T., Barbier, E. B., Bateman, I., van den Bijgaart, I., Crépin, A. S., Edenhofer, O., Fischer, C., Habla, W., Hassler, J., Johansson-Stenman, O., Lange, A., Polasky, S., Rockström, J., Smith, H. G., Steffen, W., Wagner, G., Wilen, J. E., Alpízar, F., Azar, C., … Robinson, A. (2019). Policy design for the Anthropocene. *Nature Sustainability*, *2*(1). https://doi.org/10.1038/s41893-018-0194-x

Sterner, T., & Coria, J. (2013). Policy instruments for environmental and natural resource management, second edition. In *Policy Instruments for Environmental and Natural Resource Management, Second Edition*. https://doi.org/10.4324/9781315780894

Wilson, C., & Kim, Y. J. (2018). Technology-Specific Analysis of Energy Innovation Systems. *Global Innovation Index 2018*, *Ithaca*, *Fontainebleau*, and *Geneva*, *World Intellectual*

Property Organisation (WIPO), *Cornell University*, *INSEAD and WIPO*, 115–126. https://www.globalinnovationindex.org/gii-2018-repor

Social and Technological Innovation Pathways for Low Energy Demand

Working paper for RITE March 2022

Authors: Gregory Nemet, Leila Niamir, and Elena Verdolini

Abstract

We present a framework for the analysis of low energy demand (LED) socio-behavioral and technology interventions and use it to identify the key conditions under which these interventions can be improved and become widely adopted over the next three decades. Grubler et al. (2018) made clear that adoption of a wide-variety of energy-reducing activities would achieve emissions reductions compatible with a 1.5 temperature target, to the extent that controversial carbon removal technologies would not be needed at all. While the analysis established that the scope for mitigation strategy focused on LED was much larger than previously portrayed, the paper did not discuss how realistic achieving such a scenario might be nor what processes would need to be in place to create a pathway to a LED outcome in mid-century. To provide initial insight on LED pathways, this paper focuses on three examples of LED innovation, i.e., ways for improving LED approaches and scaling them up to widespread adoption. Our scope includes socio-behavioral, technological, and business model innovation. We outline the distinct characteristics of LED innovation as well as driving forces affecting the LED adoption context. We use a framework from the innovation systems literature to analyze the functions of LED innovation in three case studies, covering: industrial efficiency, energy end-use, and energy prosumers. We use this analysis to identify barriers and enablers for scaling up these cases to become substantial contributors to a mid-century LED future. Key insights from these cases include the roles of peer effects; changes in lifestyles and norms; local knowledge and culture; knowledge and technology; enabling infrastructure and urban design; and markets and cost reductions.

1. Introduction

The Low-energy demand (LED) scenario (Grubler et al., 2018) quantitatively showed that a wide array of LED technologies and behaviors could reduce emissions over the next 30 years. They used detailed estimates of how low energy use could become across the whole swath of the economy and then used integrated assessment modeling to evaluate mid-century impacts on greenhouse gas emissions and other social indicators. Those results are important because they showed that the scope of emissions savings through lower energy use is vast, to the extent that they enabled the Paris Agreement targets to be achieved without relying on carbon removal technologies. These insights arose from the authors' distinct focus on energy services and whence energy demand arises–particularly in the context of increasing access to energy services in developing countries.

The original LED paper thus had a substantial impact on the climate community. For example, its insights were prevalent in the AR6 chapter on energy demand [cite ch5]. However, it also was limited in its scope. One prominent critique is that while the paper calculated careful estimates of energy savings, it did not make claims about how realistic achieving those savings might be (Keyßer & Lenzen, 2021). While (Grubler et al., 2018) generated comparisons of energy use in today's world to that in the LED future through integrated assessment scenario runs, it did not provide a pathway describing the mechanisms for this transition. For example, it provided only an overarching view of how digital technologies may impact energy demand from industry and adopted a quite specific focus on energy saved due to the increasing role of services in meeting consumer choices. More generally, it did not explicitly characterize how behavioral and social micro-dynamics would enable the transition to a low energy world (Cordroch et al., 2022). This set of mechanisms is particularly important given the LED scenario's emphasis on energy end-use, the role of consumers, and especially how they interact with each other. To be sure, all these lacunae are well beyond the scope of the ground-breaking 2018 paper. However, the extent to which the LED is taken seriously as a credible alternative, and complementary approach to other mitigation efforts depends on understanding how realistic reaching an LED world over three decades and that depends on better characterization of the mechanisms for an LED transition, which we describe here as LED innovation.

In this paper, we initiate the process of building a comprehensive narrative on LED innovation, that is, how LED technologies and behaviors can improve and be scaled up to become widely adopted. Following (Nemet and Greene, 2022) LED innovations are defined as "any effort to improve the level and structure of energy demand", "including LED technologies and LED services.'' We adopt the functions of innovation approach (Bergek et al., 2008) and use it to identify supporting conditions, innovation dynamics, and adoption timelines consistent with overall LED scenarios. The scope of innovation we use goes beyond a mere technological focus and includes social and business-model innovation. The goal of this line of work is the development of an overall innovation narrative consistent with LED in the context of five key drivers of change that condition innovation in low energy demand (Grubler et al. 2018) --higher living standards, urbanization, digitalization, novel services, and prosumers. This paper thus represents a first step towards the generation of narratives characterized through both quantitative indicators and qualitative descriptors to appropriately capture the many ways LED futures could unfold given the distinct characteristics of LED innovations (Nemet and Greene 2022).

The rest of the paper is organized as follows. The methods section describes the general framework for analysis we adopt, which builds on the functions of innovation systems and sustainability transition literature. We then lay out the distinct characteristics of LED innovation (section 2). In section 3, we apply our framework to three archetype case studies, and summarize the insights emerging from each case study. In section 4 we describe implications of these results for the development of a narrative on LED innovation which could guide and complement quantitative modeling of energy systems, integrated assessment, and policy. We also conclude and discuss future work in section 4.

2. Methodology and scope

2.1 Analytical approach

We adopt the same broad scope on LED as Grubler et al (2018), where buildings, transport, and industry provide a useful high-level taxonomy. While these categories help focus the research and make the results congruent with the structure of integrated assessment models, it should be noted early on that some of the most dynamic areas are those in which these sectors become coupled, such as vehicle to grid applications (Sovacool et al., 2020), as well as overall driving forces such as digitization that have pervasive effects across sectors (Wilson, Kerr, et al., 2020). Indeed, our case studies focus on LED innovation which are relevant in each of these three main sectors: insulation technologies and investment decisions in buildings; solar panels in buildings and (with electric vehicle to grid) transportation; and additive manufacturing for industry and transportation. The geographical scope is global, including both developed and developing country adoption contexts.

We adopt the definition of LED innovations from (Nemet and Greene, 2022) as “any effort to improve the level and structure of energy demand”, “including LED technologies and LED services.’’ We use this broad definition because the main goal is to generate new insights on the low energy demand by expanding the system boundary through incorporating elements such as human behavior, not only technology; considering material use impacts rather than only those of energy use; and assessing effects on inclusive wellbeing, rather than GDP. Consequently, a systems approach is most appropriate, focused on interactions and dynamics. We thus cover technological innovation, social innovation, and business model innovation, with the overall perspective that successful LED innovations are likely to involve substantial contributions from and interactions among all three.

Five key drivers of change that condition the context for innovation in low energy demand affect the development of narratives on LED innovation (Grubler et al. 2018):

1) *Higher living standards*. Rising incomes and education are raising expectations for living standards. A key component of these higher standards are preferences for clean environments, in a broad sense including water and air quality, ecosystems, and the climate.

2) *Urbanization*: more than half of the world's population lives and that share is expected to steadily grow. That trend raises the importance of urban form as a central adoption environment for LED practices.

3) *Digitalization*. Collecting, exchanging, storing, analyzing data: cheaply, quickly, connectedly is a transformative force and has major implications for LED and for LED innovation.

4) *Novel services*. In contrast to traditional energy efficiency measures as well as supply side energy systems, LED innovation often involves the provision of new energy services, even while it lowers energy use. LED practices thus involve multiple attributes and do not simply substitute for existing high energy systems.

5) *Prosumers*. An important change is the emergence of households and businesses that are not simply consumers of energy services but also producers and storers of energy (Morstyn et al., 2018). This expands the possibilities for new services and enhances the role of granularity.

Clearly, several of these five driving forces work in combination, as positive interactions, which can enhance the energy-saving effects of each of them. For example, digitalization combined with urbanization provides opportunities for a variety of novel services, especially in mobility. Conversely, these drivers of change can operate in opposition, for example in that novel services together with digitalization can increase energy demand. We note that some drivers increase demand for LED innovations, other drivers increase supply of innovation, and one, urbanization, does both (Nemet and Greene, 2022).

Our methodological approach follows the functions of innovation literature (Hekkert et al., 2007) complemented with insights from broader literature focusing on innovation systems and the measuring of innovation activities (Sagar and Holdren 2002; Gallagher et al. 2006; Hekkert et al. 2007; Gallagher et al. 2012; Gruebler et al. 2012; Miremadi et al. 2018; Hu et al. 2018; Gallagher et al. 2011; Avelino et al. 2019). The functions of innovation approach identifies seven key functions in an innovation system: knowledge development, knowledge diffusion, guidance of search, resource mobilization, entrepreneurial activities, market formation and creation of legitimacy.

This is, to the best of our knowledge, the first attempt to provide a well-rounded description of key innovations relevant in the context of a LED scenario based on an approach synthesizing different streams of innovation literature. Carrying out this effort in the context of LED-relevant innovation is important to account for differences in innovation stages and maturity of the different technologies, in the relevance of the different functions, as well as for the different role that key actors will play in LED scenarios in different sectors. Furthermore, the systematic use of this approach across three different technologies will ensure the identification of key aspects of innovation relevant for modeling in LED pathways.

2.2 Distinct characteristics of LED innovations

LED innovations include technological innovation, social innovation, and business model innovations. While there are diverse innovations within LED, together they carry a set of important characteristics which make them distinct from other types of innovation. Recent work identified ten key distinct characteristics of innovations relevant for LED (Nemet and Greene, 2022). These include:

1. Multiple attributes and new services
2. Non-financial attributes
3. Many heterogeneous adopters.
4. Peer effects and network effects
5. Small granular scale
6. Many iterations
7. Local system integration
8. Rebound effects
9. High Technological Readiness Levels, and
10. Important roles for general purpose technologies.

In addition to these characteristics, social innovations, and business model innovation relevant for LED also include an additional set of key characteristics, some of which align with the list from Nemet and Greene (2022):

1. ***Individual energy choices and behavior.*** Individuals are more than just consumers in climate change mitigation (Niamir 2019).
2. ***Peer effects and social norms.*** Community energy initiatives increase renewable and LED technology uptake by building social trust, initiative engagements, building capacity, and social capital formation (Hicks and Ison, 2018).
3. ***Social acceptance.*** Non-financial attributes of innovations affect their adoption as well as resistance to their adoption (Roddis et al., 2019).
4. ***Meanings and value.*** Meanings play an important role in enabling or constraining energy transitions. Meaning associated with individual energy users can influence

the design and deployment of energy innovations. The “NIMBY” (Not In My Back Yard) discourse (Devine-Wright, 2011). Moral values and political ideology influence climate risk perception and beliefs about the outcomes and effectiveness of climate action (Maibach et al. 2011).

5. **Ability to overcome traditional “market” failures and shift incentives for LED.** Current approaches to the provision of goods and services often do not provide the correct incentives necessary to promote LED. This has been widely discussed in the literature. An illustrative case is that associated with the landlord-tenant energy efficiency problem, whereby a landlord does not have incentives to improve the energy efficiency performance of a building given that energy saving will not accrue to the landlord, but rather to the tenant. Contextually, the tenant does not have incentives to invest in capital incentives energy efficiency improvements (e.g., new windows or insulation) because of the lack of capital, or because the capital costs associated with such improvements are higher than the (possibly) short-term benefits associated with lower energy bills in a rented house.
6. **Links to circular economy and role of new business models.** Similar examples are not only limited to energy efficiency, but also relate to demand for energy itself and to strategies of reuse and repair in the context of a circular economy.

2.3 Case study selection

We apply the comparative case study approach described above to three case studies, each focusing on one innovation relevant in the context of LED scenarios. The first case study focuses on additive manufacturing, a novel technology which holds promises of revolutionizing the provision of goods and services from certain industrial sectors. The second case study relates to individual energy decisions and the role of peer effects and social dynamics on energy investments, e.g., building insulation and energy efficient appliances. The third case study relates to prosumer behavior in the form of rooftop solar adoption and its integration with electric vehicles and neighboring energy users. Table 1 summarizes the three case studies.

Table 1. Summary characteristics of the case studies

Case study	**1. Additive manufacturing**	**2. Household energy**	**3. Solar prosumers**
Sector	Industrial	Buildings	Buildings, Transport
Innovation focus	Technical, business	Social	Social, technical, business
Distinct characteristics	Multiple attributes and new service, rebound effects, high Technological Readiness Levels, and important roles for general purpose technologies	Individual energy choices and behavior; Peer effects and social norms	Many heterogeneous adopters; peer effects and network effects; local system integration; meanings and value.
Demand reduction	Additive as opposed to subtractive manufacturing reduces material and energy input. On-site and on-demand additive manufacturing reduces need for spare parts production, and can also contribute to circularity (repair, reuse).	Investment on the building insulation and energy-efficient appliances reduces energy demand.	Production close to consumers and without combustion reduces wasted energy. Prosumers may be more energy conscious also.
Granularity	High/medium/low, depending on application and sector	High	High
Heterogeneity	Low in technology, high in business model	High	Low in technology, high in regulation and resulting business models.

3. Three LED innovation case studies

For each of the 3 case studies, we describe 1) the context within which the innovation is emerging; 2) its demand reducing potential; 3) the health of its innovation system functions; and 4) some initial indications of a successful path to scale up.

3.1 Additive manufacturing

3.1.1 Motivation and Context

Additive manufacturing (AM), also known as 3D printing, is a method of production based on a process of joining materials to make objects from 3D model data, usually layer upon layer (Aboulkhair et al 2019). AM initially developed a method for rapid prototyping, and subsequently evolved in a method for potential use in the larger-scale manufacturing, also named rapid manufacturing. AM allows the manufacture of geometrically complex structures in a single-step process, as opposed to the series of production processes required in traditional manufacturing, thus reducing design-to-manufacture time (Capegenimi 2014). Compared to traditional subtractive manufacturing methodologies such as injection molding, AM offers major cost advantages in sectors where customization matters, such as biomedical (e.g., prosthesis), aviation, and car manufacturing (Aboulkhair et al 2019). In addition, AM is believed to have significant socio-economic potential through the reshoring of manufacturing—i.e., the ability to bring back production and high-skilled, high-paid jobs to the EU and the US (Wiese et al 2020).

The first 3D printer was invented in the 1980s; since the 1990s, innovation activities in this field continued at a fast pace and brought about major technical improvements. Over the past three decades, costs of producing goods with AM have decreased, printers have become more user-friendly, and production is more efficient and of higher quality (Ngo 2018). This opens the opportunity to deploy AM on a much larger scale. Currently 3D printing has three main areas of applications in manufacturing: concept modeling, prototyping, and manufacturing tooling. In concept modeling, 3D printing is used to develop a prototype, which is subsequently brought to explore the scope for design modifications to adapt the product to customers' needs. In prototyping, 3D printing is extremely useful to reduce can help detect product flaws before they reach the manufacturing stage and enable improvements early in the design process. With respect to manufacturing tooling, AM allows manufacturers to quickly produce manufacturing tools to produce customized products, thereby allowing manufacturers the flexibility to explore new opportunities and respond quickly to production (Capgemini 2014). Recently, the potential of AM has been tested for the large-scale production of manufactured goods, including the construction sector. For example, WinSun successfully mass 3D printed a group of relatively cheap houses in China (approximately $4800 USD per unit) in less than a day (Ngo 2018).

AM thus has potential to drastically change all phases of production processes in the years to come, and to contribute to both LED scenarios and the circular economy. To do so, however, several technical and non-technical barriers need to be overcome. Furthermore, despite its advantages, AM may not be suitable and/or feasible for all sectors and all businesses. The applicability of AM will depend on a sector's specific needs, product complexity, degree of customization, and production volume (Aboulkhair et al 2019). Below we first discuss the potential contribution of AM to LED scenarios.

3.1.2 Cost and material and energy saving potential

As explained above, AM has been used in the early stages of production—product design, prototyping, and manufacturing tooling. In these stages, AM has significantly reduced both costs and energy and material use (Capegenimi 2014). Given that 3D printing is an additive technique it uses only the material needed to fabricate the part of interest; as a result, waste is minimized (Aboulkhair et al 2019). lower material demand will also be realized if and when the technique is used at large scale. However, many current applications are based on the use of polymers or plastics, which are not per se sustainable productions. Furthermore, AM raises further concerns regarding the sustainability concerned linked with (powder) material production and part post treatment (Kellens et al 2017).

Conversely, whether both production costs and energy demand will be lower in AM as opposed to traditional manufacturing techniques is still very much an open debate. With respect to overall production costs, a specific characteristic of AM is that, differently from traditional manufacturing approaches, it does not at present exhibit major economies of scale. Therefore, AM can operate without the pressure—nor the benefits—of decreasing manufacturing cost by increasing output (Baumers et al 2016). Early AM technologies were cost-competitive with traditional molding techniques only in industries where production volumes were relatively low (see for instance Sculpteo 2014). Technological improvements in printers' speed, costs as well as in the ability to optimize design to include multiple complex products in one batch is increasing the cost-competitiveness of AM to much higher volumes (Steenhuis and Pretorious 2017). Competitive volumes of up to 87,000 units have been reported in instances where part redesign is incorporated, i.e. taking advantage of the possibility for AM to produce complex parts (Atzeni et al 2010), Recent contributions show that the unit cost in mixed builds at full capacity is lower than in builds limited to a single type of geometry, and suggest that estimated manufacturing cost savings from AM adoption range from 36 to 46% (Baumers et al 2017).

The literature regarding the energy demand associated with AM—and how this compares to traditional manufacturing techniques—is scarce and fragmented. This is due to several reasons. First, energy costs are only a tiny fraction of AM costs Baumers et al (2017), for instance, estimate that energy costs represent approximately 0.26% of the total cost of

AM in their specific case study. Other costs, such as those of materials, matter more in determining AM cost dynamics. Second, notwithstanding steady technological improvements and adopting, the diffusion of this technology is still limited. As detailed below, revenues associated with AM technologies, products and services are still a very minor part of global economics activities. Cost-assessments, including those associated with energy demand, are often for specific case studies, and it is not clear how these results can be extended to large-scale production. Third, the application of AM has been mostly in the sectors of biomedicine, aviation, and car manufacturing. How the energy use trends in these sectors compare to other energy-intensive sectors, such as metallurgy, ceramics, or cement, is not clear. Fourth, energy demand from the application of AM will also depend on the level of demand from consumers. If AM reduces the costs of production, and this is reflected in lower goods prices, basic economic theory predicts that goods demand from consumers—and, consequently, energy demand from AM—will increase. Lastly, a major advantage of AM is the production of complex light-weighting structures which offer a good compromise between strength and density (Aboulkhair et al 2019). These contribute to reducing downstream energy demand in using sectors, as discussed below for the aviation industry. All this makes the estimation of energy demand and potential energy savings difficult to quantify across a wide range of sectors, applications, and products.

The available literature shows that AM technologies increase efficiency—including energy efficiency—in prototyping and custom manufacturing. Evidence on the energy savings arising from the large-scale deployment of AM in manufacturing are mixed. In the construction sector, reductions of 4 to 21% are achievable (Kellens et al 2017). Verhoef et al (2018) estimate that energy savings from the application of additive manufacturing in the aerospace sector range from 5 to 25%, with the largest effect in the use phase because of weight reduction. Extrapolation to the global energy demand in 2050, estimates reductions reach 5 to 27% of energy demand. It must be noticed, however, energy demand arising from increases in goods demand are however not factored into the analysis. This is a problem given that air travel is a highly energy- and carbon-intensive activity, whose energy demand is projected to increase significantly in the decades to come.

3.1.3 Assessing AM innovation system functions

In this section, we then look at innovation in AM through the lens of functions of innovation, to highlight distinct conditions under which AM successfully developed so far, and to identify the potential barriers to further development as well as the necessary conditions to ensure that AM contributes to LED and circularity and does not give rise to rebound effects.

Knowledge development. R&D and knowledge development, which include learning-by-searching and learning-by-doing, are prerequisites within the innovation system (Hekkert et al 2007). The first patent for the stereolithography technology (SLA) was filed in 1986 (Wiese et al 2020). This innovation was made possible by many previous research efforts, such as the invention of the computer (1940s), of numerical control machine tools as well as resins (1950s), the commercial availability of lasers, advances in photopolymerization, powder fusion, sheet lamination, computer graphics and computer aided design (CAD) and manufacturing (CAM) and related tools (1960s). The 1980s and early 1990s saw an increase in patents and academic publications. By the 1990s, several 3D technologies had been proven. However, the high cost, limited material choices, and low dimensional accuracy of these machines limited their industrial application to rapid prototyping and model making. Innovation in AM continued in the first two decades of this century. Improvement in quality made it so that AM technologies could be used to produce patterns, tooling, and final parts. The terms ‘Rapid Tooling’, ‘Rapid Casting’, and ‘Rapid Manufacturing’ emerged to indicate the use of AM production (Thompson et al 2016). Process families for AM now include seven distinct technical approaches, as classified by the Joint International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) International ISO/TC 261—ASTM F42 committee: material extrusion, powder bed fusion, vat photopolymerization, material jetting, binder jetting, sheet lamination and directed energy deposition (Vora and Sanyal 2020, Wiese et al 2020). Available 3D printers can use a range of different materials, including polymers, ceramic, or metal as input for printing processes (Capgemini 2014).

The knowledge generation in research as well as in practice was driven, and continues to be driven, both top down from industry and bottom up from individuals and industry, in research and practice (Thompson et al. 2016). Stereolithography was developed in response to the clearly identified market need to speed up the creation of design prototypes (Wiese et al 2020). In recent years, bibliometric data indicate rapidly accelerating research interest in AM, with universities being the main source of codified 3D printing knowledge and leading actors in the innovation system (Peña et al 2014). Yet, innovation in AM has been dominated by the private sector, especially when it comes to the total number of patents. Peña et al (2014) report over 90 % of the AM patents were held by firms and argue that patent protection played an important role for knowledge development by the private sector.

Knowledge diffusion. Following the development of the early AM technologies, the idea diffused that AM technologies could be used on a larger scale for the manufacturing of end-use products (Hopkinson and Dickens, 2001). The potential to turn rapid prototyping technologies into additive manufacturing significantly expanded the potential interest and potential market for these technologies. Achieving this potential, however, meant that the “prototyping mindset” must be changed, and AM technologies have to be adapted for large scale manufacturing settings. This changes the then predominant mode of innovation of the prototyping industry to that of knowledge diffusion through collaborations by the manufacturing industry (Lavoie and Addis 2018). Innovation in AM technologies is progressing, particularly focused on the development of novel materials and methods. Importantly, as earlier patents expire, manufacturers can develop new 3D printing devices and these technologies become more accessible. (Ngo 2018). An important push to 3D printing was given by the COVID-19 pandemic, which raised interest and investments in this technology given its application in medicine application, including those linked with respiratory devices

Guidance of search. This function of the innovation system informs the direction of innovative activity, and the mechanisms through which investments are guided among the different available technological options. In this respect, two specific aspects are worth mentioning. First, several governments played important roles in supporting innovation in 3D printing, both historically and more recently. In the early years of AM technology development, for example, the US government played a critical role domestically through both targeted direct funding, including for refinement of the technologies and for the diffusion of the resulting knowledge (Peña et al 2014). More recently, many governments included AM in their industrial policies, thus providing clear signals to private investors of the importance of this direction in innovation activities. These include both countries which are at the frontier of innovation activities, namely the US and Germany, but also many other countries which share an interest in AM as a means of industrial revitalization (Samford et al 2017). Major governments are setting up R&D funds, including the European Union’s Horizon 2020 program, or are developing workforce capability-building programs (e.g., Korea) (McKinsey 2017). Countries' strategies for developing and diffusing the use of AM technologies differ significantly. The US and Germany have established dedicated institutional capacity to research and develop AM technologies. The former has relied on the National Network for Manufacturing Innovation, while Germany on a well-known network of publicly supported Fraunhofer Institutes. Conversely, Canada focused on coupling the adoption of AM with existing local industrial strengths (Samford et al 2017). Private sector actors also play an important role for guidance of search through their efforts to test the cost-effectiveness and feasibility of the large-scale 3D printing is the response of certain private actors. This provides a clear indication of the willingness to upscale the technology.

Resource mobilization. Mobilization of financial resources for the early development of AM came both from private and from public funding. For instance, as described above, the US government contributed to the direct financing of early-stage research. Among the earliest investors in AM were the Department of Defense’s Navy through and the Defense Advanced Research Projects Agency (DARPA). Both provided steady funding for researchers, both in academia and industry. The US National Science Foundation also provided funding, including awards through the Small Business in Innovation and Research (SBIR) program (Peña et al 2014). Other governments also contributed to resource mobilization. However, inventors, particularly those of powder - bed fusion and binder jetting, also leveraged investments from the academic and private sectors to improve upon and later commercialize their technologies (Peña et al 2014). Various sectors have made a substantial investment in the AM innovation, technology development and diffusion, particularly in automotive and aerospace, as well as the military sector (Vora and Sanyal 2020).

Entrepreneurial activities. As illustrated above, the activities of entrepreneurial inventors played a key role in the early development of AM technologies. Initially, many of these firms were located in the US. More recently, reacting to steady growth of the AM market, multiple major material manufacturers engaged with these technologies, acquiring AM services, establishing partnerships, and developing internal knowledge. Entrepreneurial activities relate to material development, as well as the adaptation of existing processes towards higher process automation and towards integration with other production phases (Wiese et al 2020). The 2010s saw an increase in R&D funding by private actors and the entry into the AM market of several large corporations, including HP from the traditional printing business. In the most recent years, manufacturers partnered with several key universities to create innovation centers for applied R&D. This is the case, for instance, for the Advanced Remanufacturing and Technology Centre in Singapore and RWTH Aachen University/Fraunhofer Institute for Production Technology. As mentioned above, the expiration of the earliest patents on 3D technologies is opening opportunities for new (as well as established) players from various industries. For example, new design and service companies are being set up and new technologies developed, such as by BigRep and Carbon3D (McKinsey 2017).

Market formation. Since 2000, the market for additive manufacturing has experienced double-digit yearly growth. This growth has been made possible by improvements in materials and technologies, it was driven by the private sector, strongly supported by governments, and fueled by the increasing demand for customized and personalized products (Thompson et al 2016). By 2018, the market for AM products and services was over $7 billion. Yet, the penetration rate of AM technologies is estimated at only 8%, suggesting that much potential is currently untapped (Vora and Sanyal 2020). Part of the limited diffusion of AM technologies lies in the fact that small businesses often face very high barriers to the adoption of AM due to high upfront costs and major technical requirements. This suggests the need for active policy to help SMEs overcome endemic barriers to technology adoption which include lack of access to capital, lack of technical information and expertise, and difficulty with adoption and commercialization (Samford et al 2017).

Creation of legitimacy. Even with the wide-spread popularity of AM, the extensive implementation of AM is currently being inhibited by a lack of universal guidelines for metrology, inspection, and standardization. Impressive capabilities of AM would remain intangible until the finished parts could be certified as satisfactory and acceptable. This is one of the primary hurdles to overcome before AM becomes an effective component in the industrial and military toolset (Vora and Sanyal 2020). However, there are still multiple hurdles to overcome before AM becomes an effective component in the industry toolset. As AM continues to advance, the only way to ensure that these new technologies fit as reliable manufacturing capabilities is to prioritize the development of corresponding measurement techniques and calibration schedules. In collaboration with industry and academia, the U.S. Navy was one of the leading agencies that worked on multiple 3D printing projects to improve upon the abilities to support and calibrate this growing technology (Vora and Sanyal 2020). An important concern linked with the use of AM technologies is the fear of lack of cybersecurity and IP protection, as, like other digital technologies, AM is vulnerable to cyberattacks. It also does not currently benefit from adequate IP protection (McKinsey 2017).

This notwithstanding, several governments across the globe contribute to the popularization of 3D printing. This includes US government funding through the National Additive Manufacturing Innovation Institute (NAMII), a is a public-private partnership to promote 3D manufacturing technology to the mainstream US manufacturing sector, investments by the UK government as part of the Industrial Strategy, and the identification of 3D printing as a key growth driver by EU industrial policy (Capgemini 2014). The education sector is also contributing the generating legitimacy for AM technologies through, for instance, the inclusion of AM-relevant and specific training as part of undergraduate and graduate curricula (Capgemini 2014).

3.1.4 Needs for scale up for additive manufacturing

To achieve the scale up of AM in a context of LED scenarios, several key barriers need to be overcome. First and foremost, the cost-effectiveness, efficiency and cyber-security of these technologies must be proven at scale. Although AM avoids the high up-front tooling costs that traditional processes (such as injection molding) require, those advantages tend to fade quickly as production volume increases (Ngo 2018). AM with metals often remains much more expensive than traditional methods because of several interconnected factors: high materials costs, slow build-up rates, and the long machining hours that result, high energy consumption, and post processing costs. Furthermore, there is currently very limited attention to issues linked with cybersecurity and IP protection when studying AM technologies. Current-generation AM machinery is vulnerable to two especially important security issues. The first is the protection of original designs, including the identification of parts—particularly if parts are designed in ways that make them replicable after the product is sold. The second is protecting data from cyberattacks, the risks of which are increased by tighter integration with suppliers and customers (McKinsey 2017).

Second, AM demand for energy, and its potential energy savings must be thoroughly researched and assessed. Current evidence is too scarce to provide sound policy guidance. Importantly, the role AM can plan in LED scenarios is not only linked to technological feasibility or hurdles, rather is strongly dependent on how this technology will be used in practice. Understanding the interaction of AM technology with demand is of paramount importance to assess the potential contribution of this technology to both LED and low-material demand scenarios. This knowledge is currently missing, as AM technologies are often studied only from a technical point of view, ignoring the interface between technologies and actors/consumers.

Third, a related area of interest is the development of the market for printing materials. The cost of future materials is uncertain, as today many printers use proprietary ones owned or licensed by the manufacturer of the printing equipment. For AM to be applicable at scale, this would have to change, and more printing materials should become available (Cohen et al 2014).

All this would require investing heavily in background and exploratory research, engaging the future technology users in the innovation process, and exploring novel business models (Baumers et al 2016).

3.2 Case 2. Actors of change: household energy decisions

3.2.1 Motivation and context

Decarbonization of the economy requires massive worldwide efforts and a strong involvement of regions, cities, businesses, and individuals in addition to commitments at national levels (Grubler et al., 2018; Schot & Kanger, 2018; N. Stern et al., 2007). Human consumption, in combination with a growing population, contributes to climate change by increasing the rate of GHG emissions (Dietz et al., 2009). Over the last decade, instigated by the Paris Agreement, the efforts to limit global warming have been expanding. However, significant attention is being devoted to new energy technologies on both the production and consumption sides, while changes in individual behavior and lifestyle, and social norms as part of the mitigation strategy are often neglected (Creutzig et al., 2016; Niamir, Ivanova, Filatova, et al., 2020) .

Demand-side solutions for mitigating climate change include strategies targeting technology choices, consumption, behavior, lifestyles, coupled production–consumption infrastructures and systems, service provision and associated socio-technical transitions. Here we focus on the actors of change in the social innovation context of low-energy demand transition, by providing examples on the building sector.

Total GHG emissions in the building sector reported about 12 $GtCO_2$ in 2019, which 57% were indirect emissions from the generation of electricity and heat off-site, 24% were direct emissions produced on-site, and 18% were from the production of cement and steel used for construction and refurbishment of buildings (IEA, 2020). Thus, improving service provision in buildings while reducing energy demands is essential for many UN Sustainable Development Goals (SDGs). Technically, demand-side mitigation strategies in buildings could provide 78% (6.8 $GtCO_2e$) GHG emissions reduction by 2050 (Creutzig, et al. 2021). Many strategies accelerate energy demand reduction in buildings occurring at the end-use or individual building operational level. While emerging strategies for materials efficiency, such as 3D printing to minimize the materials content of structural elements, may also play a role if thermal performance and circularity can be improved (Mahadevan et al. 2020; Adaloudis and Bonnin Roca 2021).

3.2.2 Energy saving potential

Demand-side options in buildings can be grouped into avoid, shift, and improve (ASI) categories (Creutzig et al., 2022). Studies show avoid potential in the buildings sector, reducing waste in superfluous floor space, heating and energy use driven by households behavioral and lifestyle changes has been estimated at 10% and 50% (Ahl et al., 2019; Ayoub et al., 2014; Kai Kuhnhenn et al., 2020; Khanna et al., 2021; Niamir, Ivanova, Filatova, et al., 2020; van der Grijp et al., 2019). Shift to on-site renewable (prosumer renewables on rooftops) switch to lower-carbon fuels and electrification can save up to 70% GHG emissions (IEA, 2020; Mata et al., 2020; Niamir, Ivanova, & Filatova, 2020). Improve options, such as improved building envelope and technical systems, and energy-efficient appliances, may reduce GHG emissions by 40% (ranged 30–65%) (Braulio-Gonzalo & Bovea, 2017; Mata et al., 2018; Oluleye & Smith, 2016; Purohit & Höglund-Isaksson, 2017) .

Studies show household energy decisions and behavioral change potential can be as high as 50% (Creutzig et al., 2016; Dietz et al., 2009; Wei et al., 2007). Of course, there is a range in the energy savings achievable in buildings due to behavioral changes, depending on the type of end use. For example, savings from heating loads of 10-30% are possible for changes in the thermostat setting (Jaboyedoff et al., 2004; Niamir et al., 2018). Households are not making decisions in isolation: they are prone to the influence of interactions with peers in their social networks. In fact, social norms have an essential role in shaping individual decisions (Allcott, 2011; Dietz & Whitley, 2018; Jachimowicz et al., 2018; Niamir, Ivanova, Filatova, et al., 2020). Together, personal, and social norms can drive individuals to make energy-efficient decisions. Literature also indicates that behavioral factors are positively related to household energy use and conservation (Abrahamse & Steg, 2009; Chen, 2014), willingness to switch to green(er) provider, and other pro-environmental behaviors such as recycling and fuel conservation. Bamberg and

Möser in their meta-analysis found a relatively strong correlation between social norms and pro-environmental behavior ($r = 0.31$), as well as personal norms and pro-environmental behavior ($r = 0.39$) (Bamberg et al., 2007).

3.2.3 Innovation assessment

Decisions or actions that directly or indirectly reduce energy demand can be motivated by *market- and non-market forces*, and can be legally vs. socially vs. ethically binding. In order to facilitate LED transition, the broader view on the *social environment, cultural practices, public knowledge, producers technologies and services, and the facilities used by consumers* are needed to design implementable and politically feasible policy options (Niamir, Kiesewetter, Wagner, et al., 2020).

Theoretical frameworks that go beyond traditional sociodemographic and economic predictors and also consider psychological variables such as *awareness, subjective norms, and perceived behavioral control* to predict willingness to change energy-related behavior (Ajzen, 1991; Schwartz, 1977; P. C. Stern, 2000) do well. Several large surveys investigating the determinants of ASI behaviors in households in the Netherlands and Spain (Niamir, Ivanova, Filatova, et al., 2020), the OECD (Ameli & Brandt, 2015), and 11 European countries (Mills & Schleich, 2012) find that *awareness and personal and social norms* are as important as monetary factors. *Education* and income increase Shift and Improve behavior, whereas *personal norms* help to increase the more difficult Avoid behaviors.

Collective action by individuals as part of formal social movements or informal 'lifestyle movements' can significantly impact climate mitigation (Haenfler et al., 2012). The Friday-For-Future international social movement with large numbers of youths' campaigning for climate action has put pressure on policy makers in several jurisdictions to declare a Climate Emergency, a change in meaning and discourse that can alter the boundaries of what is considered politically acceptable (Szałek, 2013).

Community energy initiatives involve collective action by civil society – typically local residents and community groups - on climate mitigation to improve energy efficiency, shift to renewable energy and reduce fuel poverty, through collective ownership, benefit and control over decision-making (Creamer et al., 2018; Hicks & Ison, 2018). Community initiatives are integral to the "*sharing economy*" (Acquier et al., 2017) involving non-contractual, non-hierarchical, and non-monetized forms of interaction. For example, across Europe, the RESCOOP initiative brings together 1500 cooperatives and over 1 million citizen shareholders in energy renewable energy projects.

3.2.4 Needs for scale-up for household energy users

The application of the innovation functions framework to this case study of household energy users helps identify the following key enablers for scaling up these activities to support an LED future:

- Peer effects
- Lifestyle changes norms
- Empowering local initiatives
- Urban design (form and content)
- Regenerative culture, and local knowledge
- Policy packages: combination of soft (knowledge and awareness, and particularly encouraging package, e.g., certificate and awards) and hard policies (e.g. subsidies, collective investments options)

3.3 Case 3: Residential solar energy prosumers

3.3.1 Motivation and Context

Residential solar photovoltaics have emerged as an important consumer and producer technology over the past four decades. While early adoption in the 1980s was mostly limited to off grid cabins and other niche markets with exceptionally high willingness to pay (Hoffmann, 2006), in the 2020s solar photovoltaics are now a mainstream consumer technology that has been installed in millions of households in developed countries (IRENA, 2020). The granular aspect of solar photovoltaics has enabled solar to find applications in markets on a wide array of scales from tiny consumer devices two GW scale in deserts (Wilson, Grubler, et al., 2020). Here we focus on small scale installations, defined elsewhere in the literature as systems of less than five kilowatts (Gillingham et al., 2016). This scale and its applications create very different innovation and adoption dynamics than large-scale applications, even if the core technology, a solar module, is the same (Palm, 2018). For example, adopters are individuals or small groups living together, rather than corporations, thus they have differences in access to information, ways they collect information, and decision rules for adoption behavior (Nemet et al., 2017). Residential solar PV is one of the most prominent examples in energy of 'prosumers', an emerging configuration, in which households which typically have been seen as consumers of energy from large scale suppliers now can also play a role at certain times as producers of energy (Rathnayaka et al., 2012). Moreover, a set of complementary innovations beyond efficient solar panels are becoming affordable for households and are enhancing the potential for household prosumers to play a much bigger role than they do currently (Michaels & Parag, 2016). Thus, residential energy prosumers are an important scale up pathway to understand. Specifically, the combination of solar with household energy storage (either in standalone batteries or embedded in electric vehicles) combined with digitalization and smarter grids can enable household solar prosumers to play a much bigger role than the niche that they currently play in a low demand high energy service future (Denholm & Margolis, 2016).

3.3.2 Energy saving potential

Residential solar prosumers have strong potential for energy savings for multiple reasons. First, because the source of the energy sunlight is accessed meters away from the point of energy service delivery, i.e., in the household, losses due to the transmission and distribution infrastructure are minimal. Second, because solar photovoltaics do not involve combustion there is little generation of waste heat. Other than the absorption of sunlight by dark solar panels that is not converted into electricity. However, the possibility of light-colored solar panels with high efficiency has the potential to minimize even that waste heat effect (Lee & Song, 2021). Third, in many cases residential solar uses roof space that has very little last value once solar panels are installed. In fact, studies of property prices show that property prices are higher when solar panels are installed (Begley & Hoen, 2021; Qiu et al., 2017). Thus, the human land use impacts of solar and residential scale are minimal compared to utility scale solar. To be sure not all types of urban form can be fully powered by residential solar. In general, the higher the population density the less availability of sunlight and energy density from solar (Denholm & Margolis, 2008). However, LED practices in cities can mitigate the disparity between the areal density of energy consumption and that of incoming solar radiation.

But even with these limitations there is large potential for energy savings from solar mainly because so few roofs have been used for solar to date. In fact, in large markets such as the US, Germany, and China, less than 5% of households have solar installed. So, the potential for scale up and the potential for energy savings are large; for example, one study of the US put the rooftop potential at 38% of electricity consumption for the US (Gagnon et al., 2018). Today residential solar involves a little bit less than half of total installations the rest being large scale utility scale solar (IRENA, 2020). Scenarios and studies of future energy supply see a big role for solar including one for residential solar as well (Creutzig et al., 2017; Haegel et al., 2019). The pathway to scaling up residential solar and more importantly the ways in which this adoption might happen and how technological developments and configurations could affect how it is used are the focus of this case study.

3.3.3 Assessing the health of the seven functions of innovation systems.

We first assess the long-term scale up of residential solar by mapping the current status to the seven innovation functions. As we see in the other case studies, social innovations and behavioral aspects, especially peer effects have a large potential role to play with solar and do not fit cleanly in the seven functions of innovation systems. However, in contrast to the household insulation case study, continued technical innovation on hardware and software has the potential to play a big role in the development of residential solar even if the core solar panel device hardware is stable, mature and has clearly attained the dominant design. For example, the proliferation of household energy storage either standalone or in electric vehicles combined with digitalization especially connectivity to the grid and information flowing through the grid plays a big role in the future of solar as well.

1. *Knowledge development*. All technologies enabling solar prosumers have been developed: solar panels, energy storage, electric vehicles, smart meters, and power systems (O'Shaughnessy, Cutler, et al., 2018). The one component for which knowledge is still being developed is modeling of grid power flows to manage an increasing share of power from solar, but that is also quite well-established.

2. *Knowledge diffusion*: developed components have also become widely available. Similarly, one limit to this is widespread awareness of grid operation for variable renewables, with experienced locations more competent at managing substantial shares of renewables than emerging locations, and thus contributing to dispersion in integration costs (Heptonstall & Gross, 2021).

3. *Guidance of search*: renewables obligations, subsidies, as well as information programs (like Solsmart in the US) have all helped raise awareness and orient expectations that household solar is a growing segment. In surveys it is highly popular (Hazboun & Boudet, 2020; Roddis et al., 2019). Still the long-term guidance is not fully internalized as we describe below in legitimacy.

4. *Resource mobilization*. In many jurisdictions, resources have been fully mobilized. Financing costs for residential solar are generally quite low in developed economies, albeit not in developing ones (Schmidt, 2019). Investment in the grid for variable renewables integration requires large resources as do storage and electric vehicles, but these are all well on their way.

5. *Entrepreneurial activities*. Residential solar has many entrepreneurs. In multiple segments. For example, installers are quite small and local in Germany (Neij et al., 2017). There are 10,000 installers in the US, although a small number of large ones meet half of demand (O'Shaughnessy, Nemet, et al., 2018).

6. *Market formation*: residential solar is well on its way having passed through the niche phase and adoption having gone beyond early adopters to more mainstream consumers (Haegel et al., 2019).

7. Creation of legitimacy. The growth of the market has conferred legitimacy, such that it is now part of the policy regime (Horstink et al., 2021). Much has spilled over from utility scale solar where very large solar installations have conferred legitimacy for solar in general which residential benefits from. For example, a BNEF forecast recently headlined: “Residential solar and storage becomes the default offering in more than two markets.” Still, these have not represented monotonic progress, and in many jurisdictions growth of residential solar has stalled and been thwarted by actors who oppose further growth of solar. In a benign development subsidies have been reduced. More perniciously barriers have been erected such as loss of net metering or large fixed charges. A narrative emerges that residential solar imposes costs on non-solar users to pay for the distribution system which all benefit from. Further, peer to peer energy trading, the logical next step for prosumers (Luo et al., 2014), has not achieved legitimacy and strong political forces use extant regulations and natural monopolies to bar the inception of neighbors buying and selling electricity.

3.3.4 Needs for scale-up for solar prosumers

The application of the innovation functions framework to this case study of solar energy prosumers helps identify the following key enablers for scaling up these activities to support an LED future:

- Narrative about possibility of large amounts of solar manageable on grids.
- Peer effects to spread adoption.
- Acceleration to meet climate and LED goals.
- Enabling infrastructure for EVs
- Technology and regulations for peer-to-peer household power wheeling. Business models emerging and able to fit in regulations, eventually regs changed to allow it and later changed to encourage it.
- Establishing legitimacy, i.e. that residential solar can play an important role, and benefits all, not just the wealthy who could afford it early on, both within developed and extended to developing countries. Also clarify recycling and circularity of materials.

4. Lessons learned and implications for LED narratives

Our application of the functions of innovation systems framework to three case studies of LED innovation leads to several insights about scaling up LED innovations more broadly. We use acronyms for each case: additive manufacturing (AM), household energy users (HE), and solar prosumers (SP).

4.1 Scale up drivers

Peer effects. Both the household energy users case study and the solar prosumers case study show strong roles for peer effects. In HE, households are not making decisions in isolation, they are prone to the influence of interactions with peers in their social networks (Dietz & Whitley, 2018; Jachimowicz et al., 2018; Niamir, Ivanova, Filatova, et al., 2020); in other words, household is affected by social environment, and in particular by what people commonly do or what other people think and expect (Cialdini, 2006). In fact, peer effects and social norms have an essential role in shaping households' decisions. Peer effects and social norms might be more influential in some countries than others (Niamir, 2019; Pettifor et al., 2017). In SP, households learn from their neighbors about opportunities and risks with producing and storing their own energy. As SP technology scales up, peer effects turn into network effects as neighborhood scale energy transactions occur. Peer effects are thus central to spreading adoption and accelerating it to meet climate and LED goals.

Changes in lifestyles and norms. The HE case shows the central role that behavioral change will need to play for HE to become a core part of an LED future. Changes in social, technological, or demographic factors can also be enshrined in scenario narratives of future lifestyle change. Examples include a shift in consumption culture from owning goods to using services including through sharing economies (Vita et al., 2019), and a demographic shift from rural to urban, from physical to virtual work, and from analogue to digital (Gallic et al., 2018). Collective action and movements (e.g. local initiatives) may be necessary to enable people to change lifestyle and norms (Bamberg et al., 2015; Javaid et al., 2020; Niamir, Kiesewetter, Wagner, et al., 2020; Sunstein & Reisch, 2014). The crucial role of changes in norms is also apparent in the AM case study. Whether the scale up of AM technologies will contribute to a LED future is largely a matter of how this technology will be used in practice, and how business models will be developed. LED and sustainability consideration should be embedded in the design of business models and in the use of AM by firms and consumers. Else, AM will likely not contribute to a LED future.

Local knowledge and Culture. The HE case shows the importance of empowering local knowledge and culture in LED transformation. Cultural energy practices, local and endogenous knowledge, and natural heritage sites can act as assets for climate change mitigation, reconciliation, and recovery. We do need a call for the design and development of regenerative cultures; cultures that are consciously building the capacity of everybody in a particular place to respond and change (Wahl, 2016) .

Knowledge and technology. While hardware plays an important role in HE and SP, those cases do not depend on technology development to scale; conversely, technology improvements are central hurdles for scale up in the AM case. Elements of the scale up of AM include technology advancements, adaptation of AM to the different needs of different sectors. Importantly, AM may not be equally relevant and applicable for all sectors: its LED potential is extremely heterogeneous also across different stages and scales of production. If scale up has to happen in the context of LED, increased monitoring of energy performance and demand (and, incidentally, of material demand to address circularity and sustainability concerns) has to be carried out. Impacts on consumers' demand through potential cost-efficiency effects must be explored. Scale up will require, on the one hand, that knowledge providers such as universities partner with businesses to test the scalability of AM. On the other hand, it will also require that SMEs and businesses get involved in what now looks like a niche market.

Enabling infrastructure and urban design. Infrastructure is central to SP, because of the need to make connections, e.g. from one household to another, from the grid to decentralized generation, and from vehicles to the electricity system. Scale up of SP requires a growing infrastructure enabling this system. The possibility of large amounts of prosumer solar depends on grids being able to manage those energy flows. In a more macro way, HE also requires infrastructure development, but in this case at the scale of cities. Urban form and spatial planning could have a significant potential in end-use energy demand reduction through provisioning (shared) services, usage of material, and infrastructure access and use. Here again, using local and endogenous knowledge in urban design and planning would enable and facilitate nature-based solutions.

Markets and cost reductions. By 2050 it is plausible that AM technologies will have significantly increased their penetration rate, but at present it remains highly unlikely that their costs for mass production will be competitive with traditional manufacturing in sectors where customization is not a high priority or request by customers, unless the expectations of consumers change significantly. This notwithstanding, AM has the potential to contribute to LED scenarios. Cost reductions play a less central role in HE and SP. However, costs of solar, energy storage, and grid integration of variable renewables also are important for widespread adoption of prosumer behavior.

4.2 Policies for scale up

The three case studies point to the need to support scale up through different types of policies. For AM, policies necessary for scale up range the whole spectrum, from innovation policies to industrial policies to policies targeting. They include funding for R&D to overcome technical barriers, support for the deployment of these technologies on the ground, especially for SMEs which face high barriers, and investment in the education of both workers and consumers. Regulatory policy with respect to IP protection and cybersecurity will play a crucial role to strengthen the use of these technologies on the ground. Importantly, policies contributing to the establishment of new norms and business mindset will have to be part of the set of policy mixes which are implemented to support the scale of AM in the context of LED scenarios.

For HE, while policies potentially act as an important external (top-down) driver/barrier in households' energy decision and behavior, the role and influence of bottom-up drivers such as household sociodemographic characteristics, access to facilities and services, psychological and social factors in climate change mitigation movements are inevitable. Households' energy behavior and choices are a function of personal and social norms and the content of norms depends on the context (Niamir, 2019; N. Stern, 2016; Sunstein, 1996; Thaler & Sunstein, 2009). Climate change challenges pose major collective action problems, where a group benefits from a certain action, but no individual has sufficient incentive to act alone (Nyborg et al. 2016; Niamir 2019). Here, formal institutions (e.g., laws and regulations) are not always able to impose collectively desirable outcomes. Instead, informal institutions, such as social norms, can play a crucial role. If conditions are right, policy can support social norm changes, helping address global problems (Nyborg et al. 2016; Niamir 2019). To conclude, households are more than just consumers. In transition to a low energy demand, policies should go beyond economic cost-benefit incentives (e.g., subsidies and taxes). We suggest a policy package which is a combination of conventional, price-based policies (e.g., carbon price, taxes, subsidies); nudging and soft policies; and unbounded local-to-global regulations and policies. To design implementable and politically feasible policy options, we do need to consider the social environment, cultural practices, public knowledge, producer technologies and services, and facilities used by consumers. Various financial, social, and other instruments in the policy mix should be designed as a coherent set to reinforce each other, optimizing their joint effectiveness. Policies, such as the provision of targeted information, social advertisements, and power of celebrities for the broader public in combination with education, can be used to create more knowledge and awareness in the longer run and could accompany and reinforce the effectiveness of other stimuli, such as subsidies.

For SE, a variety of policies will be needed. These include policies that focus on a few areas. First, consider technology and regulations for peer-to-peer household power wheeling. Business models emerging and able to fit in regulations, eventually regulations need to be changed to allow it and later changed to encourage it. Second, policy is needed for establishing legitimacy, i.e., that residential solar can play an important role, and benefits all, not just the wealthy who could afford it early on, both within developed and extended to developing countries. Also, policies are needed to clarify recycling incentives and the circularity of materials.

4.3 Implications for modeling: LED pathways and narratives

Our case studies illustrate the need to complement traditional large scale modeling tools, such as integrated assessment models and energy system models, with novel tools which allow us to capture some of the key drivers of LED solutions. As apparent from the above discussion, the deployment of new technological solutions, such as AM has the potential to contribute to low levels of energy demand through increased energy efficiency. However, such technological solutions alone will not suffice, as rebound effects will most likely materialize because of increased efficiency. Developing LED pathways and associated narratives requires accounting for the role of key non-technological aspects and drives, such as peer-effects in the context of heterogeneous agents, or changes associated in lifestyles and norms, and the development of local knowledge. This is notoriously a major challenge for large-scale integrated assessment models.

Overcoming this challenge calls for two key shifts in scenario modeling. On the one hand, large scale integrated assessment models and energy system models must be complemented with modeling approaches which can more easily and better capture heterogeneous effects and the role of peer effects in technology development and diffusion. This is the case, for instance, for agent-based modeling, which has the potential to play an increasing role in informing large scale modeling exercises. On the other hand, it then becomes apparent how important it is to develop LED narratives which can not only enrich model results, but also provide the rationale for specific constraints (such as low energy demand levels) which would result from changes in lifestyle, norms, and beliefs. Both aspects represent important areas of further development for the modeling of LED scenarios in the context of large-scale integrated assessments of energy, the economy, and the environment

In addition, the modeling of complementary policy instruments targeting behavioral change and norms also need to be included in large scale assessment exercises. Currently, models are extremely limited in their ability to depict different policy instruments and mixes. This surely represents an interesting area of further model development, and a particularly important one in the context of LED pathways.

4.4 Directions for further work

This paper analyses three illustrative examples of LED innovations, i.e., ways for improving LED approaches and scaling them up to widespread adoption, to highlight key lessons learned which can guide the development of LED modeling. Our cases illustrate that technological innovation is not the sole driver of LED. Rather, socio-behavioral, technological, and business model innovation play a key role in achieving a LED future. Overall, our analysis shows that to realistically achieve a LED scenario, attention should be given to a range of non-technological, non-cost aspects of technology diffusion, such as peer-effect, changing norms and demand-side solutions, play a crucial role. Most of these are currently overlooked large-scale integrated assessment and energy systems models used to develop low-carbon pathways.

Our analysis thus represents an initial step in the process of building a comprehensive narrative on LED innovation. Clearly, important avenues for future research on LED innovation remain. First, our assessment of three distinct cases makes clear that analysis of additional cases is likely to provide further insight. Using a common framework, such as the functions of innovation systems, provides an important structure for aggregating insights from a diverse set of LED cases. This structure is important because cases will need to cover the breadth of LED innovation, which includes behavioral, technological, and business model innovation; the buildings, industrial, and energy sectors; as well as the distinct conditions in developing countries, countries in transition, and developed countries.

Second, we see strong potential for generating new insights by implementing the modeling ideas described above. We highlight the need for the combination of different modeling approaches to capture both technological and non-technological drivers of and barriers to LED innovation, as well as the necessity to develop narratives which accompany LED pathways to ground and justify model results.

Third, policymakers will benefit from more direct and context specific policy guidelines to facilitate scale up of LED practices. This includes diagnosing the presence of possible policy motivations including addressing innovation system failures, improving technology, facilitating adoption, enabling new business models, and addressing adverse consequences of successful adoption like rebound or excessive materials demand. This work will need to acknowledge the roles of local context both in adoption and policy, especially developing countries. Given the breadth of policies relevant in the three cases we cover here, we see promise in developing sets of policy components and policy mixes. Further, assembling combinations of policies over time is also promising, for example via strategic policy sequencing of LED behavioral, business model, and technological innovations.

References

Abrahamse, W., & Steg, L. (2009). How do socio-demographic and psychological factors relate to households' direct and indirect energy use and savings? *Journal of Economic Psychology*, *30*(5), 711–720. https://doi.org/10.1016/j.joep.2009.05.006

Acquier, A., Daudigeos, T., & Pinkse, J. (2017). Promises and paradoxes of the sharing economy: An organizing framework. *Technological Forecasting and Social Change*, *125*, 1–10. https://doi.org/10.1016/j.techfore.2017.07.006

Ahl, A., Accawi, G., Hudey, B., Lapsa, M., & Nichols, T. (2019). Occupant Behavior for Energy Conservation in Commercial Buildings: Lessons Learned from Competition at the Oak Ridge National Laboratory. *Sustainability*, *11*(12), 3297. https://doi.org/10.3390/su11123297

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, *50*(2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Allcott, H. (2011). Social norms and energy conservation. *Journal of Public Economics*, *95*(9), 1082–1095. https://doi.org/10.1016/j.jpubeco.2011.03.003

Ameli, N., & Brandt, N. (2015). Determinants of households' investment in energy efficiency and renewables: Evidence from the OECD survey on household environmental behaviour and attitudes. *Environmental Research Letters*, *10*(4). https://doi.org/10.1088/1748-9326/10/4/044015

Ayoub, N., Musharavati, F., Pokharel, S., & Gabbar, H. A. (2014). Energy consumption and conservation practices in Qatar—A case study of a hotel building. *Energy and Buildings*, *84*, 55–69. https://doi.org/10.1016/j.enbuild.2014.07.050

Bamberg, S., Möser, G., & Mo¨ser, G. M. (2007). Twenty years after Hines, Hungerford, and Tomera: A new meta-analysis of psycho-social determinants of pro-environmental behaviour. *Journal of Environmental Psychology*, *27*(1), 14–25. https://doi.org/10.1016/j.jenvp.2006.12.002

Begley, J., & Hoen, B. (2021). *Solar at High Noon: Solar Home Premiums in a Rapidly Maturing Market* (SSRN Scholarly Paper ID 3894549). Social Science Research Network. https://papers.ssrn.com/abstract=3894549

Bergek, A., Hekkert, M., & Jacobsson, S. (2008). Functions in innovation systems: A framework for analysing energy system dynamics and identifying goals for system-building activities by entrepreneurs and policy makers. In T. Foxon, J. Köhler, & Christine. Oughton (Eds.), *Innovation for a low carbon economy: Economic, institutional and management approaches*. Edward Elgar.

Braulio-Gonzalo, M., & Bovea, M. D. (2017). Environmental and cost performance of building's envelope insulation materials to reduce energy demand: Thickness optimisation. *Energy and Buildings*, *150*, 527–545. https://doi.org/10.1016/J.ENBUILD.2017.06.005

Chen, K. K. (2014). Assessing the effects of customer innovativeness, environmental value and ecological lifestyles on residential solar power systems install intention. *Energy Policy*, *67*(2014), 951–961. https://doi.org/10.1016/j.enpol.2013.12.005

Cialdini, R. B. (2006). Influence: The psychology of persuasion. In *New York, NY, USA: HarperCollins Publishers.* Herper Collins New York. https://doi.org/10.1017/CBO9781107415324.004

Cordroch, L., Hilpert, S., & Wiese, F. (2022). Why renewables and energy efficiency are not enough—The relevance of sufficiency in the heating sector for limiting global warming to 1.5 °C. *Technological Forecasting and Social Change*, *175*, 121313. https://doi.org/10.1016/j.techfore.2021.121313

Creamer, E., Eadson, W., Veelen, B. van, Pinker, A., Tingey, M., Braunholtz-Speight, T., Markantoni, M., Foden, M., & Lacey-Barnacle, M. (2018). Community energy: Entanglements of community, state, and private sector. *Geography Compass*, *12*(7). https://doi.org/10.1111/gec3.12378

Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G., & Pietzcker, R. C. (2017). The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, *2*(9). https://doi.org/10.1038/nenergy.2017.140

Creutzig, F., Fernandez, B., Haberl, H., Khosla, R., Mulugetta, Y., & Seto, K. C. (2016). Beyond Technology: Demand-Side Solutions for Climate Change Mitigation. *Annual Review of Environment and Resources*, *41*(1), 173–198. https://doi.org/10.1146/annurev-environ-110615-085428

Creutzig, F., Niamir, L., Bai, X., Callaghan, M., Cullen, J., Díaz-José, J., Figueroa, M., Grubler, A., Lamb, W. F., Leip, A., Masanet, E., Mata, É., Mattauch, L., Minx, J. C., Mirasgedis, S., Mulugetta, Y., Nugroho, S. B., Pathak, M., Perkins, P., … Ürge-Vorsatz, D. (2022). Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nature Climate Change*, *12*(1), 36–46. https://doi.org/10.1038/s41558-021-01219-y

Denholm, P., & Margolis, R. (2016). *Energy Storage Requirements for Achieving 50% Penetration of Solar Photovoltaic Energy in California* (NREL/PR-6A20-66970). National Renewable Energy Lab. (NREL), Golden, CO (United States). https://www.osti.gov/biblio/1327937

Denholm, P., & Margolis, R. M. (2008). Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States. *Energy Policy*, *36*(9), 3531–3543.

Dietz, T., Gardner, G. T., Gilligan, J., Stern, P. C., & Vandenbergh, M. P. (2009). Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(44), 18452–18456. https://doi.org/10.1073/pnas.0908738106

Dietz, T., & Whitley, C. T. (2018). Environmentalism, norms, and identity. *Proceedings* *of the National Academy of Sciences*, *115*(49), 12334–12336. https://doi.org/10.1073/pnas.1817487115

Gagnon, P., Margolis, R., Melius, J., Phillips, C., & Elmore, R. (2018). Estimating rooftop solar technical potential across the US using a combination of GIS-based methods, lidar data, and statistical modeling. *Environmental Research Letters*, *13*(2), 024027. https://doi.org/10.1088/1748-9326/aaa554

Gallic, T. L., Assoumou, E., & Maïzi, N. (2018). Investigating long-term lifestyle changes: A methodological proposal based on a statistical model. *Sustainable Development*, *26*(2), 159–171. https://doi.org/10.1002/sd.1727

Gillingham, K., Deng, H., Wiser, R., Darghouth, N. R., Nemet, G., Barbose, G., Rai, V., & Dong, C. (2016). Deconstructing solar photovoltaic pricing: The role of market structure, technology, and policy. *Energy Journal*, *37*(3), 231–250. https://doi.org/10.5547/01956574.37.3.kgil

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., Rao, N. D., Riahi, K., Rogelj, J., & Stercke, S. (2018). A low energy demand scenario for meeting the 1.5° C target and sustainable development goals without negative emission technologies. *Nature Energy*, *3*(6), 515–527. https://doi.org/10.1038/s41560-018-0172-6

Haegel, N. M., Atwater, H., Barnes, T., Breyer, C., Burrell, A., Chiang, Y.-M., De Wolf, S., Dimmler, B., Feldman, D., Glunz, S., Goldschmidt, J. C., Hochschild, D., Inzunza, R., Kaizuka, I., Kroposki, B., Kurtz, S., Leu, S., Margolis, R., Matsubara, K., … Bett, A. W. (2019). Terawatt-scale photovoltaics: Transform global energy. *Science*. https://doi.org/10.1126/science.aaw1845

Haenfler, R., Johnson, B., & Jones, E. (2012). Lifestyle Movements: Exploring the Intersection of Lifestyle and Social Movements. *Social Movement Studies*, *11*(1), 1–20. https://doi.org/10.1080/14742837.2012.640535

Hazboun, S. O., & Boudet, H. S. (2020). Public Preferences in a Shifting Energy Future: Comparing Public Views of Eight Energy Sources in North America’s Pacific Northwest. *Energies*, *13*(8), 1940. https://doi.org/10.3390/en13081940

Hekkert, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S., & Smits, R. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, *74*(4), 413–432.

Heptonstall, P. J., & Gross, R. J. K. (2021). A systematic review of the costs and impacts of integrating variable renewables into power grids. *Nature Energy*, *6*(1), 72–83. https://doi.org/10.1038/s41560-020-00695-4

Hicks, J., & Ison, N. (2018). An exploration of the boundaries of ‘community’ in community renewable energy projects: Navigating between motivations and context. *Energy Policy*, *113*, 523–534. https://doi.org/10.1016/j.enpol.2017.10.031

Hoffmann, W. (2006). PV solar electricity industry: Market growth and perspective. *Solar*

Energy Materials and Solar Cells, *90*(18–19), 3285–3311.

Horstink, L., Wittmayer, J. M., & Ng, K. (2021). Pluralising the European energy landscape: Collective renewable energy prosumers and the EU's clean energy vision. *Energy Policy*, *153*, 112262. https://doi.org/10.1016/j.enpol.2021.112262

IEA. (2020). *Tracking Buildings 2020*. https://www.iea.org/reports/tracking-buildings-2020

IRENA. (2020). Renewable Capacity Statistics 2020. *International Renewable Energy Agency*.

Jaboyedoff, P., Roulet, C.-A., Dorer, V., Weber, A., & Pfeiffer, A. (2004). Energy in air-handling units—Results of the AIRLESS European Project. *Energy and Buildings*, *36*(4), 391–399. https://doi.org/10.1016/j.enbuild.2004.01.047

Jachimowicz, J. M., Hauser, O. P., O'Brien, J. D., Sherman, E., & Galinsky, A. D. (2018). The critical role of second-order normative beliefs in predicting energy conservation. *Nature Human Behaviour*, *2*(10), 757–764. https://doi.org/10.1038/s41562-018-0434-0

Kai Kuhnhenn, Luis Costa, Eva Mahnke, Linda Schneider, & Steffen Lange. (2020). *A Societal Transformation Scenario for Staying Below 1.5°C | Heinrich Böll Stiftung*. https://www.boell.de/en/2020/12/09/societal-transformation-scenario-staying-below-15degc

Keyßer, L. T., & Lenzen, M. (2021). 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. *Nature Communications*, *12*(1), 2676. https://doi.org/10.1038/s41467-021-22884-9

Khanna, T., Zamora, M. D. M., Javaid, A., Löschel, A., Creutzig, F., Guias, H., Hirth, L., Callaghan, M., Haddaway, N. R., Koch, N., Laukemper, S., & Minx, J. C. (2021). Reducing carbon emissions of households through monetary incentives and behavioural interventions: A meta-analysis. *Environmental Research Letters*, *submitted*.

Lee, H., & Song, H. J. (2021). Current status and perspective of colored photovoltaic modules. *Wiley Interdisciplinary Reviews: Energy and Environment*, *10*(6), e403. https://doi.org/10.1002/WENE.403

Luo, Y., Itaya, S., Nakamura, S., & Davis, P. (2014). Autonomous cooperative energy trading between prosumers for microgrid systems. *39th Annual IEEE Conference on Local Computer Networks Workshops*, 693–696. https://doi.org/10.1109/LCNW.2014.6927722

Mata, É., Kalagasidis, A. S., & Johnsson, F. (2018). Contributions of building retrofitting in five member states to EU targets for energy savings. *Renewable and Sustainable Energy Reviews*, *93*(July), 759–774. https://doi.org/10.1016/j.rser.2018.05.014

Mata, É., Korpal, A. K., Cheng, S. H., Navarro, J. P. J., Filippidou, F., Reyna, J., & Wang, R. (2020). A map of roadmaps for zero and low energy and carbon

buildings worldwide. *Environmental Research Letters*, *15*(11), 113003. https://doi.org/10.1088/1748-9326/abb69f
Michaels, L., & Parag, Y. (2016). Motivations and barriers to integrating ‘prosuming’ services into the future decentralized electricity grid: Findings from Israel. *Energy Research and Social Science*, *21*, 70–83. https://doi.org/10.1016/j.erss.2016.06.023
Mills, B., & Schleich, J. (2012). Residential energy-efficient technology adoption, energy conservation, knowledge, and attitudes: An analysis of European countries. *Energy Policy*, *49*, 616–628. https://doi.org/10.1016/J.ENPOL.2012.07.008
Neij, L., Heiskanen, E., & Strupeit, L. (2017). The deployment of new energy technologies and the need for local learning. *Energy Policy*, *101*, 274–283. http://dx.doi.org/10.1016/j.enpol.2016.11.029
Nemet, G. F., O’Shaughnessy, E., Wiser, R., Darghouth, N. R., Barbose, G., Gillingham, K., & Rai, V. (2017). What factors affect the prices of low-priced U.S. solar PV systems? *Renewable Energy*, *114*. https://doi.org/10.1016/j.renene.2017.08.018
Niamir, L. (2019). *Behavioural Climate Change Mitigation: From individual energy choices to demand-side potential* [University of Twente]. https://doi.org/10.3990/1.9789036547123
Niamir, L., Filatova, T., Voinov, A., & Bressers, H. (2018). Transition to low-carbon economy: Assessing cumulative impacts of individual behavioral changes. *Energy Policy*, *118*, 325–345. https://doi.org/10.1016/j.enpol.2018.03.045
Niamir, L., Ivanova, O., & Filatova, T. (2020). Economy-wide impacts of behavioral climate change mitigation: Linking agent-based and computable general equilibrium models. *Environmental Modelling & Software*, *134*, 104839. https://doi.org/10.1016/j.envsoft.2020.104839
Niamir, L., Ivanova, O., Filatova, T., Voinov, A., & Bressers, H. (2020). Demand-side solutions for climate mitigation: Bottom-up drivers of household energy behavior change in the Netherlands and Spain. *Energy Research & Social Science*, *62*, 101356. https://doi.org/10.1016/j.erss.2019.101356
Niamir, L., Kiesewetter, G., Wagner, F., Schöpp, W., Filatova, T., Voinov, A., & Bressers, H. (2020). Assessing the macroeconomic impacts of individual behavioral changes on carbon emissions. *Climatic Change*, *158*(2), 141–160. https://doi.org/10.1007/s10584-019-02566-8
Oluleye, G., & Smith, R. (2016). A mixed integer linear programming model for integrating thermodynamic cycles for waste heat exploitation in process sites. *Applied Energy*, *178*, 434–453. https://doi.org/10.1016/j.apenergy.2016.06.096
O’Shaughnessy, E., Cutler, D., Ardani, K., & Margolis, R. (2018). Solar plus: Optimization of distributed solar PV through battery storage and dispatchable load in residential buildings. *Applied Energy*, *213*, 11–21.

https://doi.org/10.1016/j.apenergy.2017.12.118

O'Shaughnessy, E., Nemet, G. F., & Darghouth, N. (2018). The geography of solar energy in the United States: Market definition, industry structure, and choice in solar PV adoption. *Energy Research & Social Science*, *38*, 1–8. https://doi.org/10.1016/j.erss.2018.01.004

Palm, J. (2018). Household installation of solar panels – Motives and barriers in a 10-year perspective. *Energy Policy*, *113*, 1–8. https://doi.org/10.1016/j.enpol.2017.10.047

Pettifor, H., Wilson, C., Axsen, J., Abrahamse, W., & Anable, J. (2017). Social influence in the global diffusion of alternative fuel vehicles – A meta-analysis. *Journal of Transport Geography*, *62*(June), 247–261. https://doi.org/10.1016/j.jtrangeo.2017.06.009

Purohit, P., & Höglund-Isaksson, L. (2017). Global emissions of fluorinated greenhouse gases 2005-2050 with abatement potentials and costs. *Atmospheric Chemistry and Physics*, *17*(4), 2795–2816. https://doi.org/10.5194/acp-17-2795-2017

Qiu, Y., Wang, Y. D., & Wang, J. (2017). Soak up the sun: Impact of solar energy systems on residential home values in Arizona. *Energy Economics*, *66*, 328–336. https://doi.org/10.1016/j.eneco.2017.07.001

Rathnayaka, A. J. D., Potdar, V. M., Dillon, T., Hussain, O., & Kuruppu, S. (2012). Analysis of energy behaviour profiles of prosumers. *IEEE 10th International Conference on Industrial Informatics*, 236–241. https://doi.org/10.1109/INDIN.2012.6301138

Roddis, P., Carver, S., Dallimer, M., & Ziv, G. (2019). Accounting for taste? Analysing diverging public support for energy sources in Great Britain. *Energy Research & Social Science*, *56*, 101226. https://doi.org/10.1016/j.erss.2019.101226

Schmidt, T. S. (2019). Making electrification models more realistic by incorporating differences in institutional quality and financing cost. *Progress in Energy*, *2*(1), 013001. https://doi.org/10.1088/2516-1083/ab43a3

Schot, J., & Kanger, L. (2018). Deep transitions: Emergence, acceleration, stabilization and directionality. *Research Policy*, *47*(6), 1045–1059. https://doi.org/10.1016/j.respol.2018.03.009

Schwartz, S. H. (1977). Normative influences on altruism. *Advances in Experimental Social Psychology*, *10*(C), 221–279. https://doi.org/10.1016/S0065-2601(08)60358-5

Sovacool, B. K., Kester, J., Noel, L., & Zarazua de Rubens, G. (2020). Actors, business models, and innovation activity systems for vehicle-to-grid (V2G) technology: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *131*, 109963. https://doi.org/10.1016/j.rser.2020.109963

Stern, N. (2016). Economics: Current climate models are grossly misleading. *Nature*, *530*(7591), 407–409. https://doi.org/10.1038/530407a

Stern, N., Peters, S., Bakhshi, V., Bowen, A., Cameron, C., Catovsky, S., Crane, D., Cruickshank, S., Dietz, S., Edmondson, N., Garbett, S.-L., Hamid, L., Hoffman, G., Ingram, D., Jones, B., Patmore, N., Radcliffe, H., Sathiyarajah, R., Stock, M., … Zenghelis, D. (2007). *Stern Review: The Economics of Climate Change*. Cambridge University Press (CUP). https://doi.org/10.1017/CBO9780511817434

Stern, P. C. (2000). New Environmental Theories: Toward a Coherent Theory of Environmentally Significant Behavior. *Journal of Social Issues*, *56*(3), 407–424. https://doi.org/10.1111/0022-4537.00175

Sunstein, C. R. (1996). Social norms and social roles. *Columbia Law Review*, *96*(4), 903. https://doi.org/10.2307/1123430

Szałek, B. Z. (2013). Some praxiological reflections on the so-called ‘overton window of political possibilities’, ‘framing’ and related problems. *Reality of Politics. Estimates - Comments - Forecasts*, *04*, 237–257.

Thaler, R. H., & Sunstein, C. R. (2009). *Nudge: Improving decisions about health, wealth, and happiness*. https://scholar.google.com/scholar lookup?title=Nudge:+Improving+decisions+about+health,+wealth,+and+happiness&author=RH+Thaler&author=CR+Sunstein&publication year=2008&

van der Grijp, N., van der Woerd, F., Gaiddon, B., Hummelshøj, R., Larsson, M., Osunmuyiwa, O., & Rooth, R. (2019). Demonstration projects of Nearly Zero Energy Buildings: Lessons from end-user experiences in Amsterdam, Helsingborg, and Lyon. *Energy Research and Social Science*, *49*(January 2018), 10–15. https://doi.org/10.1016/j.erss.2018.10.006

Vita, G., Lundström, J. R., Hertwich, E. G., Quist, J., Ivanova, D., Stadler, K., & Wood, R. (2019). The Environmental Impact of Green Consumption and Sufficiency Lifestyles Scenarios in Europe: Connecting Local Sustainability Visions to Global Consequences. *Ecological Economics*, *164*(March), 106322. https://doi.org/10.1016/j.ecolecon.2019.05.002

Wahl, D. C. (2016). *Designing Regenerative Cultures*. International Futures Forum. https://www.triarchypress.net/drc.html

Wei, Y.-M., Liu, L.-C., Fan, Y., & Wu, G. (2007). The impact of lifestyle on energy use and CO 2 emission: An empirical analysis of China’s residents. *Energy Policy*, *35*(1), 247–257.

Wilson, C., Grubler, A., Bento, N., Healey, S., De Stercke, S., & Zimm, C. (2020). Granular technologies to accelerate decarbonization. *Science*, *368*(6486), 36–39. https://doi.org/10.1126/science.aaz8060

Wilson, C., Kerr, L., Sprei, F., Vrain, E., & Wilson, M. (2020). Potential Climate Benefits of Digital Consumer Innovations. *Annual Review of Environment and Resources*, *45*, 113–144.

Lessons Learned from EMF 37 with Implications and Suggestions For EDITS

February 28, 2022

Prepared By:
John P. Weyant
Energy Modeling Forum
and
Department of Management Science and Engineering
Room 260, Huang Engineering Center
Stanford University
Stanford, California 94305-4121

Prepared for:
Systems Analysis Group
Research Institute of Innovative Technology
for the Earth (RITE)
9-2, Kizugawadai, Kizugawa-Shi
Kyoto, Japan 619-0292

Table of Contents

1. Introduction and Overview 3

2. EMF 37: Deep Decarbonization & High Electrification Scenarios for North America 4

3. Conclusions 13

4. Recommendations for EDITS 15

5. Appendices

    Industry Study Group 18
    Buildings Study Group 24
    Transport Study Group 28
    Carbon Management Study Group 32
    EMF 37 -Final Round#1Reporting Template 37

Bibliography 86

1. INTRODUCTION AND OVERVIEW

Energy supply and demand considerations are both recognized as being crucially important in projecting future energy use, and in assessing efforts to reduce it and its attendant environmental and social impacts, including greenhouse gas emissions leading to climate changes and increasingly serious impacts resulting from them. As the scale of energy use has increased dramatically over the last 50 years or so, it has become increasingly important to account for these negative impacts of energy use alongside energy's role in improving human welfare through increased industrialization and mobility. Nonetheless, over this period, much more attention has been placed on understanding, analyzing, and projecting the energy supply dimensions of the energy supply rather than the energy demand elements of the energy system. This history has been driven primarily by the way energy and environmental issues have emerged in public discourse, and a lack of information and knowledge about energy demand processes and alternative energy use technologies, processes, regulations and policies.

Energy first became front page news in the 1970s as the so-called Arab oil embargo, left the world with suddenly short of oil in 1973 and the Iranian revolution did likewise in late 1979. This led to high oil prices, shortages of oil-based products like gasoline, jet and diesel fuel, leading to lines at gasoline filling stations and industrial facility shut downs. Since the proximate cause of these problems was a sudden reduction in oil supply, attention turned immediately to replacing the lost oil supplies or substituting other fuels for them. Although, a few researchers (c.c. CONAES, 1976, Weyant, 1978, and especially Louvins, 1976) put forward the idea of the reducing energy demand instead of increasing these alternative supplies, the lion's share of the media and public attention focused on energy supply side problems and opportunities. This obsession with supply side responses was further reinforced by the observation that energy supply and economic growth had been closely correlated from the beginning of the industrial revolution (say 1890) until the 1970s, leading many to conclude that unless disrupted oil supplies were replaced, severe economic consequences would imposed of the world's economies (EMF 1977).

Since the 1970s, oil security concerns have periodically waxed and waned, but energy use, largely still based on fossil fuels increased steadily despite evidence that this dependence lead to emissions of air and water pollutants that were then slowly recognized to be quite detrimental to human health and well-being. In addition, by the turn of the last century, concern about climate change had increased to the point that the negative impact of increased fossil fuel use on social impacts of climate changes on economic and social well-being became a major cause for concern and policy attention. Although this was widely understood in the scientific community by the late 1990s, it has only been over the last ten years that increases in extreme weather events can be attributed with some degree of certainty to climate change and this has captured significant media and public attention. This has led to calls for much more aggressive reductions in greenhouse gas (GHG) emissions (IPCC 2018), which creates a huge incentive to consider a much greater focus on energy demand measures to reduce GHG emissions through end-use demand reductions, as well as fuel switching and technological change on the energy demand side of energy systems around the world. The argument here is that although these policies and measures might be costly to society, especially if some important adjustment costs are included, a range of demand side adjustments seem likely to be much less expensive than many of the supply side options that have been projected to be "least costly" on the margin-meaning that not all energy demand side options will be less expensive, but many of them are likely to be so and, are, therefore, worthy of much greater attention than has occurred so far. The combined environmental, security, robustness and resilience benefits of reductions in energy demand may, therefore, in many cases be accompanied by economic benefits as well.

This story line is pursued further here using the experience so far in the initial stages of Energy Modeling Forum Study #37 on "Deep Decarbonization & High Electrification Scenarios for North America," a study with some common objectives as EDITS but different, but overlapping, overarching objectives and a narrower geographical scope. We then summarize some major conclusions from EMF 37 so far, and close with some recommendations from these conclusions for the future of EDITS and EMF 37.

2. EMF 37: Deep Decarbonization & High Electrification Scenarios for North America

The EMF 37 study on "High Electrification Scenarios for North America" was formally initiated in the fall of 2020. Although it is not explicitly focused on energy demand futures and policies, it promises to provide many insights into how low energy demand scenarios might materialize and be encouraged. Since much the effort will be focused on integrating energy demand sector and carbon management expertise and sectoral analyses and modeling approaches into the formulation and operation of country to continental scale energy systems models in North America in a way that has not been done as systematically before

This section describes the progress in the organization, design and implementation of the study desired to produce a sequential set of increasing sophisticated North American electrification scenarios for the Energy Modeling Forum (EMF) 37 exercise involving interactions between national energy and environment systems modelers and transportation, buildings, industrial and carbon management experts. It incorporates the discussions at scoping meetings in the fall of 2019, continued discussions with the steering committee and study groups, and the October 29, 2020 official kick-off meeting and a sequence of monthly meeting of the full working group that started in October 2020 and will continue through mid-2023.

The rationale for the EMF 37 study is a desire to understand the potential role for electrification under economy-wide decarbonization pathways in important energy consuming economic sectors—transportation, buildings, and industry. Much of the deep decarbonization literature points to the decarbonization of the power sector followed by the electrification of the economy as the best strategy, but there is a lack of consensus on the ultimate potential for electrification, and rate at which it can be implemented given technical, behavioral, and economic limits – and competition from other promising emission mitigation options. This study is being designed to explore the opportunities, limitations, trade-offs, and robustness of results associated with high electrification in North America.

The major motivating questions for this EMF are:

- To what extent can the transportation, buildings, and industrial sectors be electrified, particularly in the context of policies to achieve deep decarbonization and "net-zero" emissions? How might technological and behavioral change and decarbonization efforts alter the extent of electrification?
    - Beyond decarbonization efforts, what are the key drivers of electrification in the transportation, buildings, and industrial sectors?
    - How might the availability of other decarbonization options such as carbon management and low-carbon fuel sources (e.g., biofuels or hydrogen in various forms) compete with electricity to moderate the extent of electrification?
- What are the implications of high electrification scenarios on the energy system and economic and environmental outcomes in North America in reference projections and across a range of decarbonization scenarios?
- How does technological change in the power sector shape electrification pathways?

Importantly, the study is designed to engage all energy and economy-wide models as well as sectoral and technology experts forming study groups focused on transportation, industry, buildings and carbon management.

The study description and design are presented in four sections below:

- Study Structure and Process i.e., types of models and rounds of the study
- Overview of the Scenarios i.e., scenario matrices and illustrative sensitivity examples
- Scenario Details and Discussion i.e., detailed specifications
- Reporting and Submissions i.e., reporting template development and submission process

Study Structure and Process

To address the questions above, the EMF Steering Committee proposes a multi-round study that encourages the participation of economy-wide[1] and more detailed sectoral models. EMF 37 includes study groups focused on transportation, buildings, industry, and carbon management, with the possibility of adding study groups on other important dimensions as the study progresses (e.g., energy efficiency, behavior, power sector, and low-carbon fuels). As with any

[1] As used here, economywide includes both general and partial equilibrium models with comprehensive energy sector coverage.

EMF, the goal is to identify robust insights and areas for further development. Insights from this study will be derived from the combination of economywide models, detailed sectoral models, and depth and breadth of the study groups.

Table 1 below presents an example process through three rounds of scenario development, modeling, data submissions, and analysis with a “Beta-Round” completed and a Round #1 now well under way. As recent EMF’s have demonstrated, an initial trial submission round helps resolve reporting issues across models (e.g., consistency with units and variable definitions). For this study we proceeded with the beta round involving the economywide models running two scenarios with default or modeler’s choice assumptions about electrification: one with and one without emission reductions. In addition to working out reporting issues, this beta round will allow us to begin the dialogue between the modeling teams and the study groups to help flesh out the design of the scenarios for subsequent rounds, and determine how best to pass data between economy-wide and sectoral models. For example, the economywide models can run scenarios pass emissions price or quantity data to the single-sector models.

Subsequent rounds are adding scenarios developed during the beta round and Round #1 in consultation with the study groups. The details are discussed in the next section. To broaden the types of models participating in subsequent rounds while maintaining important consistencies within the study, a critical deliverable from the economy-wide all energy models includes the production of data to be used in sectoral models. For example, detailed, single-sector models (e.g., power sector only models), may take the outputs of the economywide models as exogenous inputs (e.g., electricity demand, emission prices). In other cases, highly aggregated economywide models lacking technological detail (e.g., electric vehicles) may calibrate to the electrification or emission reduction profiles from economy-wide all energy model results. The details and timing of these data passes will be a subject of discussion during the beta round and may continue to be refined as the study progresses.

Given the potential complexity of the scenarios and data dependencies between models, it is prudent to consider the possibility of a Round 3 to refine scenarios and resolve any issues identified in Round 2. A Round 3 would also give the sectoral models an opportunity to incorporate updated input assumptions from the economywide models from Round 2 (e.g., energy/electricity demand, fuel prices). Note that the sectoral models may be re-run one final time with the Round 3 inputs from the economy-wide models.

The anticipated study schedule, presented in Table 1 below, includes roughly monthly virtual meetings that are intended to be shorter and more frequent than the in-person meetings in a traditional EMF study. The meetings are organized by round and allow for a rotating focus between the overall results from the economy-wide models and focused meetings for the study groups.

Overview of the Scenarios

Table 2 presents the Round 1 scenario matrix. There are five sub-matrixes for this round, the first is the matrix for the "overall scenarios" and the next four are the scenarios matrixes for each study group.

The first four columns of the "overall scenarios" matrix indicate what combination of assumptions should be taken from the four study groups, either the 'all advanced' assumptions or the default 'ref' assumptions from the models. Each row then indicates a scenario with a different combination of assumptions across study groups. The last five columns indicate the overall CO2 emissions target, covering five emissions pathways: a *No Target* scenario plus three emission reduction pathways to *Net Zero* CO_2, and one emissions pathway to *Net Zero GHG*.[2] Intersecting the technology assumption row with the emissions pathway column specifies a scenario. The beta round scenarios included the top row model default (ref) technology assumptions for a '*No Target*' scenario (dark gray), and a '*Net 0 by 2050*' scenario (light gray), both of which will be repeated for Round 1. The remaining required Round 1 overall scenarios fill out the '*Net 0 by 2050*' column and include the '*All Advanced*' scenarios from each study group (blue) and a scenario that interacts the '*All Advanced*' assumptions from each study group in a single scenario (green). Since these scenarios rely heavily on the scenarios designed by the study groups, we will cover them at the end of the Round 1 series of meetings.

The next four sub-matrixes for the individual study groups have the same columns for the emissions targets (noting that some do not show the optional columns). The columns to the left indicate the combinations of assumptions about technology, complimentary policies, and preferences that define each scenario row. The orange scenarios are specific to the study group, and the blue scenarios are the '*All Advanced'* scenarios that carry over to the overall scenario matrix. The Carbon Management Study Group (CMSG) includes assumptions about CCS, hydrogen and direct air capture (DAC). The Transportation Study Group (TSG) includes assumptions about advanced vehicle technology, enabling complimentary policies, and shifting preferences resulting in behavioral change. The Industry Study Group explores industrial energy efficiency; materials efficiency; industrial applications of renewable energy, hydrogen and carbon capture utilization and storage (CCUS); and industrial electrification. Finally, the buildings study group (BSG) explores building energy efficiency and electrification through market-based strategies that directly and indirectly support preferred technologies through improved cost and performance, and standards-based strategies that specify minimum

[2] The emission reduction scenarios are specified as linear reductions beginning in 2020 and reaching Net Zero CO2 (or GHG) emissions by 2050, 2060, or 2080 (green columns). For the purpose of this study, we propose to assume an 800 MMT CO2 per year carbon sink from land use, land use change, and forestry from 2020 forward. This assumption provides some head room for models to reach the Net Zero targets (see next section for a detailed emissions breakdown). Figure 1 illustrates the three pathways for the US; Canada and Mexico will have similar trajectories.

performance levels that technologies must meet. The storylines and specifications for these study group scenario assumptions are included in the appendices to this report.

Table 1
Updated EMF 37 Study Schedule

Month	***Meeting Focus***	***Objectives***
September 27th	Round 1 kick-off	SC provides high-level overview of design & review of SG scenarios. SC outlines schedule for Round 1. After: Modelers (re)submit beta round scenarios using data template by Nov 4. Modelers assess implementability of Round 1 scenario guidance. Complete BSG scenarios.
November (5th)	***BETA ROUND SCENARIOS DUE***	
November (19th)	Clarify round 1 scenario implementation and assumptions	Evaluate full set of beta results (reporting errors, insights). Answer questions with SG's about implementing round 1 scenario assumptions. SG's discuss/present ideas for key figures and result evaluation metrics to inform priority data submission. Finalize data template. After this meeting, modelers should kick off round 1 scenarios and submit results.
January (7th)	***ROUND 1 OVERALL SCENARIOS DUE*** *(SG scenarios accepted)*	
January (21st)	Round 1 scenario overview and power sector	High level overview from round 1 results incl. power sector details. Develop key figures and metrics of total economy and energy system results as well as power sector figures.
February (4th)	Scenarios and Data Help Session	Open "Office Hours" to discuss scenarios and data template issues
March (4th)	***ROUND 1 SG SCENARIOS DUE*** *(Overall scenarios revisions accepted)*	
March (18th)	Transportation and buildings deep dive	More detailed presentation and discussions for each sector. Develop key figures for each sector. Preliminary discussion of changes for round 2.
April (8th)	Industry and carbon management deep dive	
April (22nd)	*All ROUND 1 scenario revisions accepted*	
May (6th)	Discuss modeling and scenario changes for round 2	Present/Distribute revised key figures reflecting discussions from previous meetings and including revised round 1 scenario submissions. Discuss modeling and scenario changes for Round 2.
round 2		
R2 Mtg 1	carbon management round 2 scenarios	
R2 Mtg 2	transportation round 2 scenarios	
R2 Mtg 3	buildings round 2 scenarios	
R2 Mtg 4	industry round 2 scenarios	
R2 Mtg 5	economy-wide final scenarios + sensitivities	
final ?		
R3 Mtg 1	carbon management final scenarios	
R3 Mtg 2	transportation final scenarios	
R3 Mtg 3	buildings final scenarios	
R3 Mtg 4	ecomomy-wide final	
	Paper drafts	

Table 2. Round 1 Final Scenario Matrix

Overall Scenarios								
CMSG	Trans	Ind	Bldg	No Target	Net 0 by 2050	Net 0 by 2060	Net 0 by 2080	Net 0 GHG by 2050
Ref	Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R1	0by60.Ref.R1	0by80.Ref.R1	0GHGby50.Ref.R1
Adv	Adv	Adv	Adv	NT.All-Adv.R1	0by50.All.Adv.R1	0by60.All-Adv.R1	0by80.All-Adv.R1	0GHG0by50.All-Adv.R1
Adv	Ref	Ref	Ref	NT.CMSG.Adv.R1	0by50.CMSG.Adv.R1			
Ref	Adv	Ref	Ref	NT.TSG.Adv.R1	0by50.TSG.Adv.R1			
Ref	Ref	Adv	Ref	NT.ISG.Adv.R1	0by50.ISG.Adv.R1			
Ref	Ref	Ref	Adv	NT.BSG.Adv.R1	0by50.BSG.Adv.R1			

CMSG Scenarios						
Technology						
CCS	H2 Prod.	DAC	No Target	Net 0 by 2050	Net 0 by 2060	Net 0 by 2080
Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R1	0by50.Ref.R1	0by50.Ref.R1
None	Ref	None		0by50.CMSG.1.R1	0by60.CMSG.1.R1	0by80.CMSG.1.R1
Adv	Ref	Ref		0by50.CMSG.2.R1	0by60.CMSG.2.R1	0by80.CMSG.2.R1
Ref	Adv	Ref		0by50.CMSG.3.R1	0by60.CMSG.3.R1	0by80.CMSG.3.R1
Ref	Ref	Adv		0by50.CMSG.4.R1	0by60.CMSG.4.R1	0by80.CMSG.4.R1
Adv	Adv	Adv	NT.CMSG.Adv.R1	0by50.CMSG.Adv.R1	0by60.CMSG.Adv.R1	0by80.CMSG.Adv.R1

Transportation				
Technology	Policy	Preference		
Adv. Tech	Policy Enlbmt	Behv. Chg.	No Target	Net 0 by 2050
Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R1
Adv	Cons	Cons		0by50.TSG.1.R1
Cons	Adv	Cons		0by50.TSG.3.R1
Cons	Cons	Adv		0by50.TSG.4.R1
Adv	Adv	Cons		0by50.TSG.2.R1
Adv	Adv	Adv	NT.TSG.Adv.R1	0by50.TSG.Adv.R1

Ref.R1erence Scenario
Model Default Policy Scenario
All Adv.R1anced - Interaction Scenario
All Adv.R1anced - Study Group Scenario
Study Group Scenario
Optional Scenario

Industry					
Technology					
EE	Mat. Eff.	RE/H2/CCUS	Ind. Elec	No Target	Net 0 by 2050
Ref	Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R1
Adv	Ref	Ref	Ref		0by50.ISG.1.R1
Ref	Adv	Ref	Ref		0by50.ISG.2.R1
Ref	Ref	Adv	Ref		0by50.ISG.3.R1
Ref	Ref	Ref	Adv		0by50.ISG.4.R1
Adv	Adv	Adv	Adv	NT.ISG.Adv.R1	0by50.ISG.Adv.R1

Buildings						
Mrkt Bldg Tech Policy		Standards Bldg Policy				
Elec	EE	Elec	EE	No Target	Net 0 by 2050	
Ref	Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R1	BS1 - Reference
Adv	Ref	Adv	Ref		0by50.BSG.1.R1	BS2 - Agg-Elec
Adv	Adv	Ref	Ref		0by50.BSG.2.R1	BS4 - Market-EEE
Adv	Adv	Adv	Adv	NT.BSG.Adv.R1	0by50.BSG.Adv.R1	BS3 - Agg-EEE
Ref	Ref	Adv	Adv		0by50.BSG.2.R1	BS5 - Stnd-EEE
Adv	Ref	Ref	Ref		0by50.BSG.2.R1	BS6 - Market-Elec
Ref	Ref	Adv	Ref		0by50.BSG.2.R1	BS7 - Stnd-Elec
Ref	Adv	Ref	Adv		0by50.BSG.2.R1	BS8 - Agg-EE

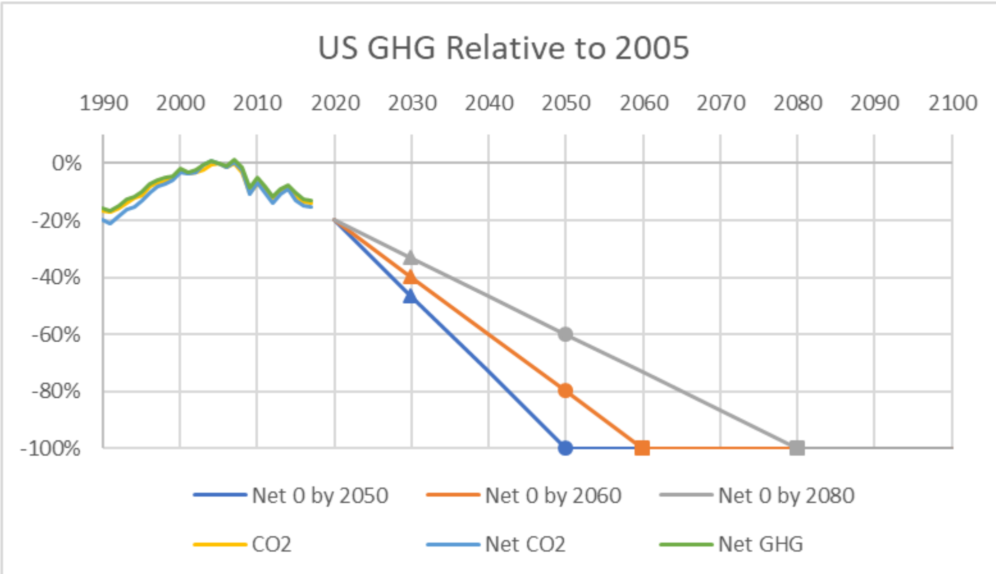


Figure 1. Illustrative decarbonization pathways for the US (Note: Canada and Mexico will follow similar straight-line reduction trajectories from 2020 to net zero.)

Scenario Details and Discussion

Reference Scenario

The reference scenario assumes no new federal climate policy. To the extent practicable, modelers should include existing federal incentives for energy technologies as well as state policies (e.g., RPS, RGGI, AB32). In light of the rapidly changing economic circumstances, for the beta and first rounds, models should use their existing reference scenario. Future rounds may encourage baseline calibration to a forthcoming EIA Annual Energy Outlook scenario (e.g., AEO 2021).

Decarbonization Dimension

Net Zero Pathways

The decarbonization pathways are defined as linear reductions from 2020 to Net Zero emissions by 2050, 2060, or 2080. The targets are specified as CO_2-only and include the following source categories: fossil fuel combustion, non-energy use fossil fuels, and industrial process emissions. Non-CO_2 GHG emissions are not included.

Because not all the EMF 37 models include land and forest carbon sinks, in this study the Net Zero annual emissions targets are converted into gross CO_2 emission targets. Converting the net emissions goals to goals framed as a reduction in gross fossil carbon emissions requires consideration of the full array of U.S. GHG sources and sinks.

For models that do not endogenously estimate LULUCF, we will assume a constant sink of 800 $MtCO_2$ per year. This assumption provides 800 Mt CO_2 per year head room for models to reach the Net Zero targets and translates into a maximum reduction of combustion and non-combustion CO_2 emissions of 87% in the final year (e.g., 2050, 2060, or 2080) as shown in Table 3.

A more detailed sectoral breakdown of the US GHG Inventory is presented in Table 4. Note that emissions from biomass consumption (e.g., wood, ethanol and biodiesel) are embedded with the LULUCF category.

While the emissions pathways are specified as CO2 only, models should assume that the resulting carbon price or shadow price on carbon should also be applied to non-CO2 greenhouse gases. In addition, we include a net-zero GHG by 2050 sensitivity scenario to shed additional light on the differences between net-zero CO2 and net-zero GHG targets.

Banking and Borrowing: No banking or borrowing is allowed in meeting the reduction targets. While allowing full flexibility with banking and borrowing may be more efficient, it would obscure some of the key issues we want to explore in this study. First, we are interested in what the net-zero energy system and economy look like, and banking would allow models to avoid meeting that target. Second, we are also interested in the 2030 results along the path towards net-zero. With banking and borrowing, and carbon prices following a Hotelling path, the near-term results and the initial carbon price are driven by long-term technology assumptions

Additional Assumptions

International Policy Outside of North America: The focus of this study is on high electrification scenarios for North America under different rates of decarbonization. To minimize the trade effects in global models or models that represent international trade, assume that all regions face the same carbon price as found in North America.

Offsets: These scenarios assume no international or domestic offsets or tax credits of any kind.

Reporting and Submissions

We plan to use the IAMC reporting format (Excel spreadsheet) with submissions uploaded to the IIASA scenario database. This system has worked well for other model comparison exercises including EMF 32. A draft reporting template and instructions for setting up an account and submitting results will be distributed in the June/July timeframe.

Reporting years: Required reporting years are: 2020 (or first base year of model after 2020) and every 5 years from 2025 to 2050, inclusive. Additionally, modelers are encouraged to report results at the native time step of their model (down to an annual time step) and out to the year 2080.

Reporting regions: Sub-national results are relevant to this study as energy demands and supplies will differ across regions. We will attempt to identify some common sub-US (-CAN, -MEX if applicable) reporting regions (e.g., census or census plus key states). Modelers are welcome to report results at the state level. Additional guidance will be provided for global models on how to report multi-country regions outside of North America.

Table 3. US CO_2 emissions and LULUCF sink and assumptions (Mt CO_2)

Gas/Source	Inventory 2005	Inventory 2018	Projections / Targets 20-50/60/80
CO2 (gross)	6,132	5,425	800
Fossil Fuel Combustion	5,741	5,032	
Non-Energy Use	140	135	
Industrial Process	252	258	
Land Use, Land-Use Change, and Forestry (Sink)	-815	-774	-800
Net CO2 Emissions (Sources and Sinks)	5,317	4,651	**0**

Table 4. Summary of US CO_2 emissions inventory in 2005 and 2018 (Mt CO_2e).

INCLUDED SOURCES	Inventory	
Gas/Source	2005	2018
CO2 (gross)	6,132	5,425
Fossil Fuel Combustion	5,741	5,032
Transportation	1,856	1,821
Electric Power	2,400	1,753
Industrial	850	833
Residential	358	337
Commercial	227	247
U.S. Territories	50	41
Non-Energy Use of Fuels	140	135
Industrial Process	252	258
Iron and Steel Production & Metallurgical Coke Production	70	43
Cement Production	46	40
Petroleum Systems	12	37
Natural Gas Systems	25	35
Petrochemical Production	27	29
Other	70	74
Land Use, Land-Use Change, and Forestry[a] (Sink)	-815	-774
Net CO2 Emissions (Sources and Sinks)	5,317	4,651
EMBEDDED or EXCLUDED		
Wood Biomass, Ethanol, and Biodiesel Consumption (embedded in LULUCF sink) [a]	231	329
Non-CO_2 GHG (excluded)	1,260	1,252

Source:Excerpt from US EPA GHG Inventory Report, Table ES-2.

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

Reporting variables and template: A list of reporting variables with common names and definitions will be developed and agreed upon before the beta round. The variable list developed by the Integrated Assessment Modeling Consortium will serve as a starting point. New variables will need to be added to cover the detailed, sector-specific information for this study as well as variables that may need to be passed back-and-forth between models.

Reporting template and data repository: Modelers will upload results in an Excel spreadsheet format to a data repository hosted by IIASA. The repository compiles all of the results into a single database and can perform submission checks of the data.

Modelers' Choice Scenario Options

The discussion above notes several potential modelers' choice options. The analysis, interpretation, and documentation of modeler's choice scenarios may require reporting variables that are not contained in the standard database template. The best way to report non-standard variables is to enter the custom data into an existing, unused variable and note the new definition of the variable in the 'comments' tab of the data template.

Modeler's choice scenarios may address a variety of other areas such as additional alternate technological dimensions or the inclusion of non-CO_2 GHG's under decarbonization targets.

3. Conclusions

This short snapshot of the current status of EMF 37 leads to a number of insights regarding progress made towards its objectives so far and strategies for achieving them more fully over the next year or two.

i. Creating a Study Structure that Gives Equal Footing to Systems Modelers and Sectoral Energy Demand Experts has Started the Process of Improving the Energy Demand Content of the Models and the Scenarios they Produce

Through the monthly meetings of the full working group, the first two sets of model comparison exercises and related activities, the sectoral energy demand experts have learned more about what demand side information and methodologies are included in the models individually and collectively. And the monthly meetings of the individual study groups have enabled them to make both scenario specification and demand sector formulation recommendations to the modeling teams which has led to transfer of data and relevant prior analyses to the modeling teams and some initial model refinements. In this effort it has been important to not let the systems modelers be the final decision makers regarding what questions and scenarios are to be investigated.

ii. In Implementing This Process, it has Been Important to Recognize and Adapt to the Very Different Structures of the Participating Models and the Range of Purposes for Which They Were Initially Designed.

Although it is important to analyze results across all the models for a group of carefully designed benchmarking scenarios, it is also important not to force all the models to try to run all the more detailed study group scenarios. In fact, comparing the results from the models with more aggregated energy demands and processes with models that have - or are adding in such detail - is another important product of the process for the participating modeling teams and those who consume the results from the study.

iii. In Moving Forward, the Study Can Take Advantage of All the Data and Terminology Standardization That Has Taken Place so Far as Well as the Early Scenario Comparisons to Help the Systems Modelers and Energy Sector Demand Experts to Increase the Collaborations Between the Study Groups and the Systems Modeling Teams Further and Produce Scenarios That Should Are More Realistic and Actionable to Model Users

The results of this process will make the results from the individual models and the scenarios they produce more useful, help users understand which results are robust across models and scenarios, as well as why key results differ between models, and to identify high priority areas for future research. It will be important to add more input from the business community regarding new business models that could move technology introduction and market diffusion much more rapidly in net zero GHG scenarios

iv. In Moving Forward, it Will be Important to Establish a Set of Thematic Cross-Cutting Groups to Refine and expand the Current Scenarios and Help Communicate The Study Results to A Broad Set of Analysts Corporate Strategy and Policy Advisers

Likely Candidates are; (1) the Electricity Sector, (2) Hydrogen Production, Transportation and Use, (3) Technology Costs and Market Dynamics, (4) Consumer Behavior, Policy and Regulatory Assumptions, (5) non-Climate Driven Polices (those on air pollutants, water and land use), and (5) Private Sector Strategies and Behavior. These groups would further enrich the study design and participate in producing the publications at the end of the study.

v. In Order to Accomplish The Goal of Helping to Set Future Research Priorities it Will be Important to Use the Groups of Participants to Keep Track of Things That Would Like to See Improved in the Models be it Better Data, Better Modeling Methods, Better ways to Deal With Uncertainties, Etc.

With All the Activity Being Put Into Better Scenarios and Models the Study Will Rely on both Systems Modelers, and Especially the Study Group leaders to Keep Track of their most critical future research priorities. In the rush to complete publications it is easy to forget areas where all the models could use further improvement.

4. Recommendations for EDITS

Although the goals and objectives of EMF 37 and EDITS are different in a couple of important ways, the two studies share a number of similar research challenges in seeking to make the analytical tools used for deep decarbonization scenario development more used and useful. The two major differences are in the foci and scope of the two studies are: (1) The EMF 37 study is addressing the role of high electrification in net zero GHG scenarios and EDITS is focusing on low energy demand scenarios, which could have GHG benefits as well as other benefits like reductions in lower air and water pollution, and energy security improvements, and (2) the EMF 37 study is focusing primarily on the United States, whereas EDITS is global in scope.

Both EMF 37 and EDITS start with the premise that the existing modeling tools may not be fully adequate to investigate the kinds of very rapid transition scenarios now being considered because they were developed during a period when more gradual transitions were being considered. In many ways, the modeling community could evolve towards being better able to analyze more rapid transition scenarios at its own pace, but the participants and sponsors of the two studies understand that this pace would likely be too slow to provide decision makers at all level with timely advice on what to do over the next decade or two and the consequences of not acting on a timely basis are likely to be very costly, leading to either not achieving policy objectives, and/or achieving them at a cost that strains their ability to achieve other high priority objectives.

This common objectives leads both studies to seek input from research communities outside the transitional energy and environmental research communities, who generally not participated in the work of the traditional modeling and have not been seriously consulted by this community. The common assumption is that the perspective of – and alternatives methods developed by - these stakeholders and research communities could be used to improve the existing models in a way that could make their results more useful and actionable to decision makers. This leads to a number of recommendations for EDITS from EMF 37, some of which are still challenges for EMF 37 as well as described above:

i. First and Foremost, the Biggest Challenge Faced by both Studies is Getting Input and Advice From the most Important External Research Communities into the Work Plans in a Meaningful Way

The first part of this challenge is to identify all the possibly relevant research and stakeholder communities and both studies have made a good first order attempt to do so, but with the learning that has taken place and emerging trends in technologies and institutional innovations, now is the time to reconsider this challenge. The second part of this challenge is to continue to create a level playing field or “safe space” in which these communities can interact. All too often, representatives from these communities have been consulted at the beginning of an individual modeling study or model inter-comparison and see most of the advice received ignored and they not consulted again until after the study has been completed, and the advice that is ignored is not even noted in the final reports on the work. In some ways that is understandable, but given the objectives of EMF 37 and EDITS this is simply unacceptable and both studies have worked hard to prevent it. However, as talk of common model scenarios and protocols have started to emerge there is the danger in both studies that the modeling teams will dominate what is done without getting additional input from the most important external research and stakeholder communities.

ii. In Terms of Identifying and Engaging all Relevant External Research Communities there are Several Additional Groups That Have Not Yet Been Included in One or the Other or Both of the Two Studies

One research community that has not yet been fully consulted in either study is the full spectrum of researchers who study human behavior from anthropologists to social psychologists to behavioral economists. These communities can be especially critical in identifying trends and interventions that are outside of the usual energy markets framing used by energy systems modelers where energy prices and quantities are presumed to drive changes. Another omitted relevant research community consists of those who study the behavior of institutions from political scientists to corporate strategy experts to market design specialists. A third relevant research community that could be usefully brought in is the sustainable finance community who have begun focusing on the “finance-ability” of the investments required to execute the transition as opposed to simply assuming that the capital required can be attracted at very favorable (usually almost risk free) rates as is typically assumed.

iii. In Terms of Identifying and Engaging all Relevant External Stakeholder Communities there are Several Additional Groups That Have Not Yet Been Included in One or the Other or Both of the Two Studies

One such community is the corporate “cleantech” community which now includes publicly traded enterprises whose main focus is on introducing and marketing low cost alternatives to fossil field based energy and land use technologies. The contributions of these stakeholders would not only be technology expertise, but examples of new business models designed to create new industries which already have their own capital and superior credit ratings. One of many examples of this would be Tesla which has grown from a startup company to becoming one of the top ten companies in the world by market capitalization (recently hitting the one trillion US dollar mark). But there are also other firms in the EV, renewables, battery, low emissions electric generation systems sectors with similar potential. The second additional stakeholder could be cleantech entrepreneurial community including both the entrepreneurs and the public (e.g., ARPAe in the US) and private institutions that support them (e.g., venture capitalists and Breakthrough Energy Ventures). This innovation eco-system has provided a much more rapid pathway from startup to high value public enterprise then has existed before and a large number of ventures at this stage could become the next Tesla, SunPower or Exelon, etc. These companies and the ones mentioned in (ii) could be used to refine and calibrate the learning curves, and new technology diffusion algorithms included in the extant models which are generally driven by recent product sales of production capacity without looking at what is going on in the pipelines that will shape these trends in the near- to medium-term.

iv. There are also Likely to be Significant Synergies Between the New Research and Stakeholder Community Perspectives that Could Enable the Energy and Land-Use Systems to Go Further Beyond Recent Trends

A starker version of this point is now being seen in the growing admonishment that "we can't use the old tools to solve the new problems." Areas where synergies could be important include getting more input from behavioralists into new cleantech business models, and political and market design concepts into the policy debates providing the motivation for these new research directions.

v. Finally, while a small group of people has tried to coordinate what is going on in EMF 37 with what is going on in EDITS so Far, the Stage is Now Set for More Active Co-Coordination and Collaboration Over the Next Year or Two as the Two Studies Mature Further

This effort would range from more frequent and interactions between a broader set of participants to some benchmarking of scenarios and protocols to developing a set of joint scenarios and/or protocols which would enrich both studies further. At this point, enough learning, community building, and infrastructure has been developed in the two studies, that there is likely some bandwidth available to pursue greater coordination and collaboration. Moreover, it is important that this bandwidth be used wisely to yield maximum benefits.

Appendix A

Scenarios for Deep Decarbonization of Manufacturing[3] (DDM)

EMF 37 Industrial Sector Group

July 9, 2021

Four scenarios to capture different policy / technology routes for DDM, plus one “all of the above” scenario that combines the first four scenarios, are proposed. They are proposed as part of an experimental design approach to modeling; “*If this happens in industry, what are the implications in the entire energy/carbon system*?” They are intended to explore the “integrated” component of the integrated assessment models (IAMs) in round 1. The proposed industrial scenarios (IS) are:

- IS1: Enhanced Energy Efficiency
- IS2: Enhanced Material Efficiency
- IS3: Industry Specific Technologies
- IS4: Enhanced Electrification
- IS5: All of the above – i.e. IS1-4 combined

Recognizing that the IAMs all may endogenize DDM actions in various ways and to varying degrees, the idea behind these scenarios is to encourage modelers to capture the impacts of these actions in as consistent a manner as possible. For example, some models may have some industry specific technologies explicitly represented, like CCUS in Cement, whereas other models may not. The narratives and the table below provide a formal systematic guidance on developing scenarios for DDM. The implementation of these scenarios into modeling frameworks is subject to the interpretation of the modeling teams and structure and system boundaries of their respective models.

Depending on the first round of results, the ISG will work with individual model teams in round 2 to expand on the “assessment” component of the IAMs to explore issues surrounding marginal cost of industrial actions. In other words, the actions specified in the scenarios are be economic if they have a marginal cost that is lower than what the IAM projects in a net-zero scenario. If these industrial scenarios have large impacts on projected marginal cost, then the underlying costs of these industrial scenarios needs to be explored further in round 2. This is particularly true of IS3 and IS4.

Each scenario has different assumptions that are specific to eight different industrial sectors:

- Pulp & Paper
- Iron & Steel
- Bulk Chemicals
- Cement & Lime
- Petroleum Refining
- Aluminum

[3] These scenarios focus on energy/emissions from end uses in manufacturing and not energy/emissions from agriculture, construction or mining. The scenario narratives and table below are based on the EMF37 ISG’s review of E. Worrell and G. Boyd, (June 2021) “Bottom-up Estimates of Deep Decarbonization of U.S. Manufacturing in 2050,” revise and resubmit to the *Journal of Cleaner Production*. The model teams are encouraged to use this paper as supporting materials in interpreting these scenarios.

- Glass
- Light[4] Industry (any manufacturing not listed above)

Most, but not all, models in EMF37 represent these sectors individually which will allow for the treatment of differential impacts of the scenarios on different industrial sectors.

IS1: Enhanced Energy Efficiency

This scenario suggests that when society gets "serious" about climate change, so does the business sector. Increased emphasis on climate policy will likely increase businesses' desire to increase their focus on strategic energy management[5] to address climate related business risk; non-price incentives from utilities. Other policies and programs (Energy Star, ISO, utility based SEM, etc.) are likely to accelerate adoption of existing energy efficient technologies for current processes that don't fit into IS2 through IS4. Models may have both exogenous trends and endogenous choices, i.e. price induced end-use efficiency either via explicit end-use and process technologies, parametric representation (i.e. demand or substitution elasticities), or a combination.

The table below suggests potential energy efficiency improvements that are likely to be feasible by 2050. If the growth rates of projected energy efficiency, represented by a decline the energy intensity (energy/output ratio), in the reference case in a particular model (NT.REF) exceeds the values presented below for a particular sector, then no additional efficiency should be included. In the Cement industry for example, the table below assumes a 38% reduction in energy intensity (34% existing technology and 4% new). This is consistent with a -1.6% rate of intensity growth. If a model projects a -1.0% intensity change then an additional 0.6% would be included. If the model projects -2.0% then there is no incremental efficiency in cement and they would not make any adjustments for cement, i.e. do not lower efficiency levels. If a model's reference case projects a lower level of energy intensity improvement, then the scenario should include additional efficiency. If a model projects a -1.0% intensity change, then an additional 0.6% would be included. If the model projects -2.0% then there is no incremental efficiency in cement, and no adjustments would be made for cement, i.e. do not lower efficiency levels.

We realize that there isn't likely to be a simple parameter that can implement IS1; technology rich models might need to adjust technology performance assumptions or behavioral parameters (e.g. logit curves) to approximate the assumptions in this scenario, while parametric models might change Autonomous Energy Efficiency AEE rates.

IS2: Enhanced Material Efficiency

Whether you label this scenario material efficiency, circular economy, or structural change it has been well understood and documented that the mix of industrial activity has a large impact on energy use and associated emissions. Most IAMs do not endogenize the mix of industrial activity, and if they do, they most likely use historical input-output tables. This scenario explores the types of structural shift that may come directly from climate policy, e.g. changing clinker use in cement, and those that are part of

[4] It should be noted that within this sector there are some larger energy users; food processing and metal based durables being the most obvious.
[5] This term is being used in the broadest sense of the word.

broader issues, such as increasing recycling to reduce solid waste. The main thrust of this scenario is based on recognizing the connections between climate and materials production/use, which is the most energy and carbon intensive part of manufacturing. This scenario is likely driven by sets of complementary policies on material demand, recycling, and consumer behavior.

Increased availability of recycled materials to replace virgin feedstocks, driven by consumer demand/acceptance and supporting policy will have a major impact on paper, steel, chemicals (plastics), aluminum, and glass. Models that endogenize the choice of recycled feedstocks should compare the changes in these sectors with the results in their respective reference cases. Similar to IS1, model teams may need to adjust cost, performance, or adoption to reflect these higher uses of recycled feedstocks. This increase will reduce the linkage between the economic activity of these sectors and the primary material use. The lower growth in primary material product can also be represented simply by a shift in the material intensity of industry output or directly as shift in the energy intensity of those sectors.

In addition to shifts toward recycled feedstocks to produce products, some industries will experience lower demand for primary products. Steel output declines as transportation modes and usage shifts; product design reduces plastics and other manufactured material use (packaging, etc.). Some of these shifts are very specific, e.g. the Cement industry can reduce the amount of clinker in its final product, but this will require complementary policy changes in building codes and construction design. This can be represented as a shift over time in the material (energy) intensity of cement demand.

IS3: Industry Specific Technologies

Some industries have particular process needs or conditions that can make particular DDM activities more attractive. We include renewables, H_2 and CCUS in IS3. Some of these advanced applications are largely untested, at least commercially, so the cost implications are probably more important than in IS1 and IS2. This could be explored more in round 2, time permitting.

Renewables are limited to biomass; we do not include renewable generation of electricity in IS3 since this should be endogenous to the IAMs and other modeling frameworks. While siting is important and industry may have a role to play, we do not want to attempt to include on-site industrial PV, etc. in this scenario. Some sectors, like paper, chemicals, cement, and light industry either have access to self-generated biomass or have other conditions that make biomass attractive.

H_2 use in steel and chemicals has some particular advantages. H_2 could be used in other industries for some other furnace types and heating applications, but we assume that electrification will be more attractive (see IS4). This is in line with the specific thrust of EMF 37. However, if H_2 industrial technologies are endogenous to a model, then those assumptions should remain unchanged.

CCUS will likely have cost advantages where high concentration CO2 streams are available. This suggests that if CCUS can be implemented in the power sector, it would likely be cost effective in selected industries. This includes steel, chemicals, and cement. If CCUS technologies for industry are endogenous to a model, then those assumptions should remain unchanged.

IS4: Enhanced Electrification

Enhanced industrial electrification can best be thought of in terms of low, medium, and high temperature applications. Cost effectiveness will track temperature; some low temperature applications using heat pumps are currently cost effective and more efficient. Most heat in light industry is low temperature and some paper industry applications are medium temperature, making these sectors attractive. Electric boilers for hot water and low pressure steam can be cost effective, depending on relative natural gas vs electric prices, i.e. "spark spread." We anticipate that carbon prices and grid decarbonization will likely make the spark spread sufficient for all low and medium temperature opportunities. Higher temperature furnaces, e.g. glass, can also be electrified but cost effectiveness is less clear. EAF Steel is an obvious application, but is also tied to assumptions in IS2 and IS3, making a clear distinction difficult. Other types of steel heating for rolling can be electrified. We propose IS4 in round 1 as a very high electrification scenario, including some high temperature uses, but costs for models that represent these choices explicitly will need to be explored in more detail in round 2.

<u>IS5: "All of the above" IS1-4 combined</u>

This is the "all in" scenario for DDM. How actions from IS1, IS2, and IS3 combine to impact IS4 is important. In the absence of actions to reduce industrial fuel and electricity use, the level of electrification alone will be much higher. This would likely put more pressure on the power grid. Complementary efficiency polices (IS1 and IS2) should reduce that pressure, particularly whether or not the industrial actions have much impact on marginal carbon costs. We will be very interested to see the extent of this when round 1 results become available. If the model teams will be asked to run industrial scenarios in tandem with other working group scenarios, we suggest that IS5 be used for that exercise.

Scenario		Pulp & Paper	Iron & Steel	Chemicals	Cement & Lime	Petroleum Refining	Aluminum	Glass	Light Industries
IS1	**Energy efficiency**	40% efficiency improvement in fuel demand 30% savings on electricity	Energy efficiency improvement by switching to Best Available Technology (BAT) of 39%	Potential energy savings of 19% with currently available technology Potential savings of 31% with advanced technology	Potential for energy efficiency improvement with current technology at 34%, A further 4% potential savings with technology currently under development	Potential of 14% efficiency improvement with current technology, 26% additional energy savings with technologies that are in various stages of R&D	Limited potential of about 10% beyond the energy savings in the reference case.	Additional potential is estimated at 33% Technologies under development could add another 9% savings	Potential savings of 25% for fuel end uses, and 30% for electric end uses
IS2	**Material Efficiency**	No demand reduction, as material efficiency is offset by a move away from plastics Increased use of *recycled fiber* from 37% to 56% by 2050 will reduce fuel demand by 15%	Share of recycled steel increases to 90 % by 2050 because EAFs can make larger product slate thanks to DRI. Iron production declines to 16 Million mt/year because the U.S. is producing less steel and/or more scrap	Increased material efficiency in product design and recycling varies from 7% up to even 55% Plastic recycling decreases the energy used to make plastic by 25%–55%	In line with global IEA scenarios, we assume that the clinker-to-cement ratio can be reduced to 70%, from 92% now	This sector is handled endogenously by the EMF models so the models should use their estimates for fuel demand	Using part of the exported scrap domestically allows primary smelter production to decrease by about 25%	About 11 mt of glass waste is produced in the United States. Increasing the recycling rate would reduce emissions by 2 mmtCO_2 energy use by 7%	Demand will be reduced by 10% (on average) across all other industries
IS3	**Renewables**	Biomass-based CHP units increase efficiency allowing all integrated mills to operate fully on renewables 15% use of renewables in stand-alone paper mills	The share of renewables in the steel industry will be very limited due to process requirements.	Up to 15% savings due to shifting to biomass-based feedstocks Other forms of direct use of renewable energy provide up to 5% of energy	Up to 30% use of biomass fuels, although as much as 20% is already bio-based	Biofuels offset up to 15% of refinery production. . We do not assume further internal use of renewable energy	No specific opportunities identified	No specific opportunities identified	25% of heat demand can be met by renewables (e.g. in food industries)
	Hydrogen	No value of Hydrogen use	Half of remaining iron production is replaced by hydrogen-based DRI-production.	In line with The IEA estimates hydrogen could reduce CO_2 emissions by 10% in 2050	No application of hydrogen assumed in lime and cement kilns	Furnaces in a refinery can be fired with (self-generated) hydrogen	Limited potential for furnaces to be converted to use hydrogen. Electrification may be more attractive.	Hydrogen could be used as fuel. Electrification may be more attractive.	Hydrogen would be a less attractive compared to electrification and renewables
	CCUS	No use of CCUS due to location mills.	Half of remaining iron production is produced in smelt reduction plants with CCUS (resulting in emission reductions of 80-90% compared to current primary production process)	CCUS to contribute to an emission reduction of 20% of emissions	CCUS using calcium-looping would reduce emissions by 90% CO_2 curing of concrete may reduce emissions by 300 kg/mt cement	Centralized CCUS from hydrogen plant used as internal fuel	No role	No role	No role

Scenario		Pulp & Paper	Iron & Steel	Chemicals	Cement & Lime	Petroleum Refining	Aluminum	Glass	Light Industries
IS4	**Electrification**	Electrification leads to a 22% fuel use reduction (half from electric boilers, and the other half shared between heat pumps and direct electric drying).	Electrification due to increased use of EAFs and electric furnaces (induction or plasma) resulting in 14% reduction in fuel and 69% increase in electricity	Up to 20%–25% of current fuel use could be replaced by electric heating	Too early to evaluate the feasibility of this application for the US	Electrification is not attractive	For primary smelters, electricity is already the key energy source. Heating furnaces can be electrified (as some are already).	Full electrification of large furnaces possible by 2050	50% reduction of fuel use in heat (30% by electric boilers and 20% from heat pumps or Mechanical Vapor Recompression).

Appendix B

Scenarios for Deep Decarbonization of Buildings (DDB)

EMF 37 Building Energy Demand Study Group

November 2021

To understand the “potential role of electrification in economy-wide decarbonization pathways,” it is necessary to understand the potential decarbonization contributions from buildings.

From the literature it is well understood that building carbon emissions can be reduced through both energy efficiency and electrification, although for the latter to have a decarbonization effect it is necessary for the power system to decarbonize as well. Furthermore, electrification without energy efficiency will put more demands on the power system and thus require more investment in clean generation technologies, transmission infrastructure, and distribution infrastructure. Such effects can be especially pronounced in cold climates with electrified space heating—absent simultaneous investments in insulation and other envelope improvements as well as efficient cold climate heat pump technology, the per-building peak power requirements (in winter) could be large enough to drive significant distribution system investment needs.

The speed and magnitude of building decarbonization are also impacted by policy approaches. Will electrification and energy efficiency be encouraged and achieved through market-supportive policies such as R&D or industrial policy that creates more advanced and/or lower cost technologies and incentivizes adoption through monetary incentives and educational outreach; or through standards-based policies that reduce technology choice and effectively mandate fuel-switching and more-efficient appliances, more-efficient envelopes, and energy-conscious building designs; or both?

Table 1 outlines these two dimensions of building decarbonization—Decarbonization Technology (i.e., Electrification and/or Energy Efficiency) and Decarbonization Strategy (i.e., Reference, Market, Standards, or Aggressive Policies).

Under Decarbonization Technology, the electrification column focuses on fuel switching, that is, the choice to stop using natural gas or other non-electric fuel for a specific end-use and switch to using an electric appliance instead. While electric technologies are typically more efficient than their non-electric counterpart, we are not counting the fact of a switch as “energy efficiency” here—in the fuel-switching context “energy efficiency” would relate to an additional choice to select a more-efficient electric option, e.g., a heat pump water heater, induction stove, or highly efficient heat pump for space conditioning. As a decarbonization approach, energy efficiency also encompasses fuel-agnostic choices such as the amount of roof or wall insulation and type of windows, as well as more-efficient non-electric technologies.

The Decarbonization Strategy dimension asks the EMF 37 modeling teams to partition the options they have for modeling increased electrification and energy efficiency in buildings into two buckets:

5. **Market:** Strategies that directly and indirectly support preferred technologies in the marketplace by improving technology performance, lowering costs, providing energy-based labeling, or providing direct incentives, rebates, tax credits, or technical assistance.

6. **Standards**: Strategies that specify minimum performance levels that technologies must meet to be eligible for the marketplace, minimum performance levels or electric-technology requirements for new buildings or existing buildings, and restrictions on new or existing natural gas service connections.

Thinking of each option in the Market and Standards buckets as an "on" state, Table 1 labels the Reference strategy as all identified options being "off," that is, model default assumptions which are likely to represent current policy and technological trends but no other interventions. The Market Strategy then turns "on" all options placed in the Market "bucket," the Standards Strategy turns "on" all options placed in the Market "bucket," and finally, the Aggressive scenario asks modeling teams to turn on all available options that fall into either of the two buckets. Note that this scenario framework purposefully does not include any levers related only to customer behavior. In our experience, while models can describe the impact of a change such as "customers simply express more preference for electric technologies or smaller homes," it is not clear how such a change would be affected outside of interventions that actually make those choices more attractive.

Table 1: Building Decarbonization Strategies

		Decarbonization Technology	
		Electrification	Energy Efficiency
Decarbonization Strategy	Reference	• Reference assumptions about fuel choice and switching for non-electric end-uses (e.g., space heating, water heating, clothes drying, cooking)	• Reference assumptions about appliance and building envelope efficiency, for both electric and non-electric technologies
	Market	• Advanced technologies • Lower costs • Energy labels and other information • Incentives, rebates, and/or tax credits	• Advanced technologies • Lower costs • Energy labels and other information • Incentives, rebates, and/or tax credits
	Standards	• Restrictions on fuel choice through codes and standards • Building-level emissions performance standards • Restrictions on natural gas service connections	• Restrictions on technology choice (favoring more efficient technologies) through codes and standards • Building-level energy performance standards
	Aggressive	• Market & Standards Policies	• Market & Standards Policies

The dimensions described in Table 1 are used to define eight EMF 37 Building Decarbonization Scenarios in Table 2. The scenarios are designed to highlight the potential co-benefits of deploying EE alongside electrification. As such, there is only one EE-only scenario included, which is intended as a comparison point to show how much decarbonization EE could achieve on its own. Also, while above we spent some time differentiating between market-supporting and standards-based policies, the size and complexity of the EMF 37 work has led us to recommend just four core scenarios for exploring building contributions, three of which simply turn all options “on” or “off” in various combinations. For a fourth scenario, the Study Group recommends looking at how much of the “Aggressive” gains can be captured by “Market”-supporting policies alone.

Table 2. EMF 37 Building Decarbonization Scenarios (proposed). The four scenarios highlighted at the top of the table are to form the core of the analysis—we ask that all capable modeling teams submit results for these four scenarios.

Scenario	Name	Electrification	Energy Efficiency	***Purpose***
BS1	**Reference**	Reference	Reference	*Comparison point*
BS2	**Agg-Elec**	Aggressive	Reference	*Maximum electrification if ignore EE*
BS3	**Agg-EEE**	Aggressive	Aggressive	*Maximum buildings contribution*
BS4	**Market-EEE**	Market	Market	*What if only market-influencing policy tools are used to encourage electrification and EE?*
BS5	Stds-EEE	Standards	Standards	*What if strict standards are applied without improving technology and reducing costs?*
BS6	Market-Elec	Market	Reference	*What if market-influencing policy tools are used to encourage electrification and EE is ignored?*
BS7	Stds-Elec	Standards	Reference	*What if standards are applied to enforce electrification and EE is ignored?*
BS8	Agg-EE	Reference	Aggressive	*Maximum energy efficiency if ignore electrification*

BS1: Reference (Reference)

For this scenario, we expect modeling teams to use their default assumptions, which are likely to include current policies and reference technology assumptions. Current policies are represented at different levels of resolution in different models, with variation in both types and jurisdictions of policies that are represented or even representable in different modeling frameworks. Technology assumptions may also vary quite a bit model to model, given the absence of comprehensive projection data sets for this sector. However, we generally expect modeling teams to at least be able to represent current energy efficiency levels and energy service costs.

BS2: Aggressive Electrification (Agg-Elec)

Policy makers pull out all the stops to encourage and even mandate decarbonization through electrification. However, they do not provide the same level of support for energy efficiency such that electric resistance technologies for, e.g., water, space heating, and cooking, are encouraged just as much as more efficient technologies, e.g., heat pumps and induction stoves. There are no additional incentives for envelope improvements so electric technologies are likely to be dropped directly into existing buildings with little insulation and leaky windows. Efficiency levels of non-electric technologies also evolve under Reference conditions. Under this scenario significantly more energy and peak power capacity is required from power grids to support the decarbonized, but inefficient, building stock.

BS3: Aggressive Electrification and Energy Efficiency (Agg-EEE)

Policy makers are all-in on building decarbonization, making the necessary R&D and other investments to improve technology choice and lower adoption costs for consumers as well as mandating that the marketplace only offer efficient electric technologies that support societal goals for a fully decarbonized economy supported by affordable and accessible energy. Energy efficiency and electrification are promoted together, such that building standards require tight, well insulated envelopes, all adopted appliances are the most-efficient electric technologies with better performance characteristics than today's options and at lower cost, all new buildings are electric-only, and some (if not most) existing neighborhoods also transition to being electric-only over various timeframes. Retrofits may be actively required by building performance standards in some jurisdictions.

BS4: Market Electrification and Energy Efficiency (Market-EEE)

In the United States it is often difficult to obtain broad-based support for mandated change. Therefore, policy makers stay away from mandates. They leave current codes and standards programs in place, but do not step up their stringency and in no case do they require fuel switching for new or existing buildings. Instead, the focus is on R&D and industrial policy, EnergyStar and similar building-level information and outreach, along with direct monetary support for preferred technologies through rebates, tax credits, technical assistance, and other incentives to guide the building stock toward decarbonization. Customers respond by adopting more high-efficiency electric and non-electric technologies that are lower in absolute and direct customer costs. Building envelope and overall design improvements are also supported and adopted. Natural gas and other fossil fuel appliances are likely to retain significant, although shrinking, market share as efficient electric technologies may be supported more (through both electrification and energy efficiency incentives) than efficient non-electric technologies (energy efficiency incentives only).

Appendix C

Transport Study Group

Transport: Goals for Round 1 Scenarios

- Focus on drivers rather than outcomes
- 3 dimensions to explore (details next slide):
  - Technology Advancements and Availability
  - Policy (define broadly: vehicle incentives, increased fueling infrastructure, reducing barriers to adoption, system-level optimization, etc.)
  - Behavior (define broadly: telework, mobility as a service, increase in active forms of transportation such as biking and walking, etc.)
- See what the models do under scenarios crafted to somewhat align.
  - Not all models will capture everything
  - Goal is to see these differences, make changes in subsequent rounds
  - Harmonize input assumptions when possible

U.S. DEPARTMENT OF ENERGY OFFICE OF ENERGY EFFICIENCY & RENEWABLE ENERGY 1

Full Transportation Scenario Matrix

Combinations	Technology Advancements	Policy Enablement	Behavior Change
1	Conservative	Conservative	Conservative
2	Conservative	Conservative	Aggressive
3	Conservative	Aggressive	Conservative
4	Conservative	Aggressive	Aggressive
5	Aggressive	Conservative	Conservative
6	Aggressive	Conservative	Aggressive
7	Aggressive	Aggressive	Conservative
8	Aggressive	Aggressive	Aggressive

U.S. DEPARTMENT OF ENERGY OFFICE OF ENERGY EFFICIENCY & RENEWABLE ENERGY 3

Round 1 Suggested Scenarios: 1, 5, 7 & 8

Combinations	Technology Advancements	Policy Enablement	Behavior Change
1	Conservative	Conservative	Conservative
2	Conservative	Conservative	Aggressive
3	Conservative	Aggressive	Conservative
4	Conservative	Aggressive	Aggressive
5	Aggressive	Conservative	Conservative
6	Aggressive	Conservative	Aggressive
7	Aggressive	Aggressive	Conservative
8	Aggressive	Aggressive	Aggressive

Scenarios 2 and 3 will be helpful for diagnostic purposes and should also be included if possible.
*Still need to hit 0 by 2050 target economy-wide. Transport narrative applies to transport itself.

Scenario 1: Narrative for Model Implementation

- **Essentially your model's BAU set of assumptions for transportation technologies, policies, and behavioral changes. Tech assumptions ideally aligned across models (see detailed inputs shared by Page Kyle from GCAM)**

- **Technology Advancement:**
  - Conservative: cost reductions and performance improvements in line with historical trends and BAU scenarios, incremental improvements in technology availability and charging/refueling infrastructure technologies (BAU availability expansion, no groundbreaking improvements like extreme fast EV charging, wireless charging, hydrogen refueling options, etc.),
- **Policy Enablement and System-Level Changes:**
  - Conservative: No new transportation sector-specific policies (carbon price fills in gap)
- **Behavioral Changes:**
  - Conservative: No major behavioral changes for vehicle occupancy, passenger miles, mode choice (e.g., walking, micromobility, MaaS), vehicle ownership and vehicle size preferences, system-level efficiency (like traffic flow optimization, platooning, etc.), access to transit, e-commerce, or other futuristic solutions (drones, hyperloop, etc.)

Scenario 5: Narrative for Model Implementation

- **Enhanced technology advancement based on more optimistic projections and sustained cost reductions (policy and behavior aligned with scenario 1)**

- **Technology Advancement:**
  - Aggressive: rapid cost reductions and performance improvements (e.g., batteries at $50/kWh in a decade or so, hydrogen at $3 kg, etc., biofuels competitive with fossil fuels), major improvements in charging/refueling infrastructure technologies (ubiquitous EV charging, widespread H2 refueling, extreme fast EV charging, wireless charging,, etc.), rapid expansion of the availability of hybrid-electric, battery electric, and fuel cell electrification options in multiple transportation subsectors (e.g., locomotive, non-road, marine, and aviation), advancements in automation and digitization to optimize intermodal movement of people and goods
- **Policy Enablement and System-Level Changes:**
  - Conservative: No new transportation sector-specific policies (carbon price fills in gap)
- **Behavioral Changes:**
  - Conservative: No major behavioral changes for vehicle occupancy, passenger miles, mode choice (e.g., walking, micromobility, MaaS), vehicle ownership and vehicle size preferences, system-level efficiency (like traffic flow optimization, platooning, etc.), access to transit, e-commerce, or other futuristic solutions (drones, hyperloop, etc.)

Scenario 7: Narrative for Model Implementation

- **Incorporate technology advancements and transportation policy changes to enable system-level improvements.**

- **Technology Advancement:**
  - Aggressive: rapid cost reductions and performance improvements (e.g., batteries at $50/kWh in a decade or so, hydrogen at $3 kg, etc., biofuels competitive with fossil fuels), major improvements in charging/refueling infrastructure technologies (ubiquitous EV charging, widespread H2 refueling, extreme fast EV charging, wireless charging,, etc.), rapid expansion of the availability of hybrid-electric, battery electric, and fuel cell electrification options in multiple transportation subsectors (e.g., locomotive, non-road, marine, and aviation), advancements in automation and digitization to optimize intermodal movement of people and goods
- **Policy Enablement and System-Level Changes:**
  - Aggressive: Any additional transportation policy that your model includes, zero-emissions vehicle mandates as early as 2030-2035, bans on internal combustion engines in city centers, congestion pricing, LCFS, biofuel blending mandates (e.g., 100% SAF by 2050), production tax credits for clean fuels, consumer incentives, infrastructure rebates and government investments, and removal of any barriers to adoption of clean technologies. Consider removal of any policies that directly or indirectly favor transportation using privately owned vehicles (e.g., parking subsidies) and production/consumption of fossil fuels (e.g., tax credits, loan forgiveness, accelerated depreciation). If possible, also consider changes in infrastructure and urban redesign to encourage mobility options (e.g., reducing parking lots and parking spaces to optimize for pedestrians/cyclists/micromobility). To the extent possible, consider any other futuristic scenario that could significantly alter future transportation systems to improve efficiency (e.g., use of drones for all urban delivery, proliferation of 3-D printing to reduce shipping demand).
- **Behavioral Changes:**
  - Conservative: No major behavioral changes for vehicle occupancy, passenger miles, mode choice (e.g., walking, micromobility, MaaS), vehicle ownership and vehicle size preferences.

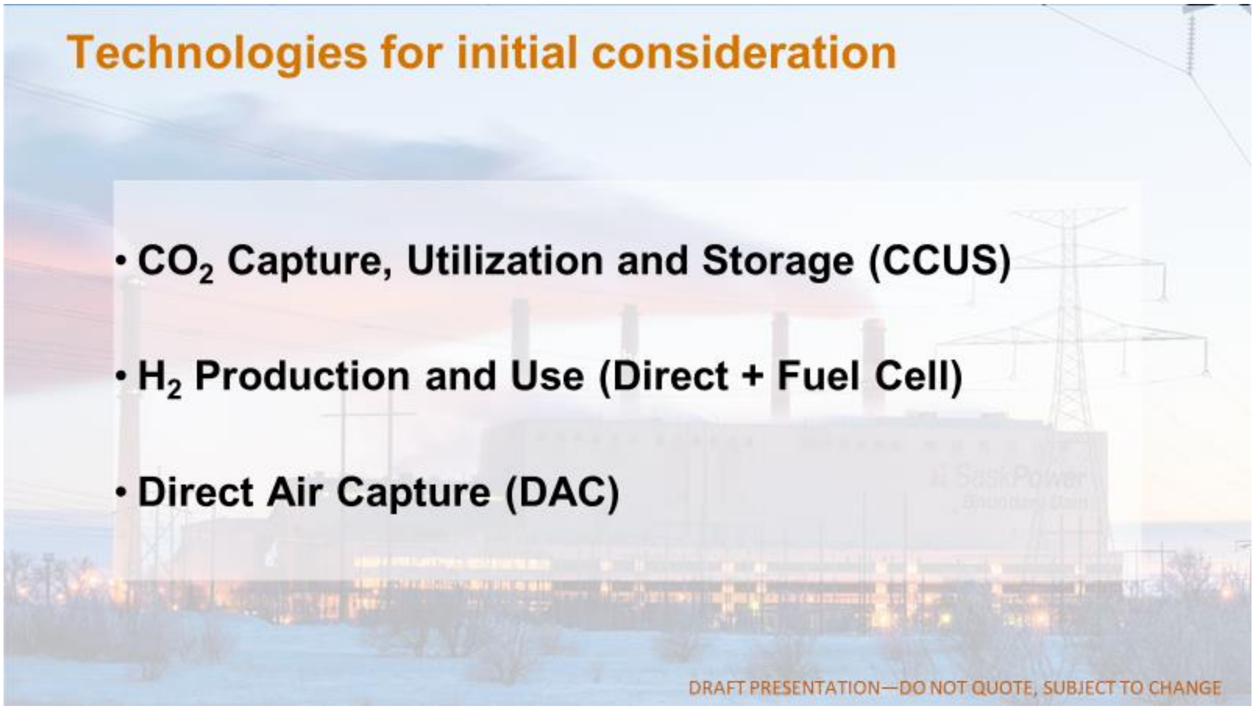
Scenario 8: Narrative for Model Implementation

- **All-in from a technology, policy, and behavior to reduce transportation emissions as much as possible, remove any barrier to clean transportation technologies. Bounding case of how far we can get**

- **Technology Advancement:**
  - Aggressive: rapid cost reductions and performance improvements (e.g., batteries at $50/kWh in a decade or so, hydrogen at $3 kg, etc., biofuels competitive with fossil fuels), major improvements in charging/refueling infrastructure technologies (ubiquitous EV charging, widespread H2 refueling, extreme fast EV charging, wireless charging., etc.), rapid expansion of the availability of hybrid-electric, battery electric, and fuel cell electrification options in multiple transportation subsectors (e.g., locomotive, non-road, marine, and aviation), advancements in automation and digitization to optimize intermodal movement of people and goods
- **Policy Enablement and System-Level Changes:**
  - Aggressive: Any additional transportation policy that your model includes, zero-emissions vehicle mandates as early as 2030-2035, bans on internal combustion engines in city centers, congestion pricing, LCFS, biofuel blending mandates (e.g., 100% SAF by 2050), production tax credits for clean fuels, consumer incentives, infrastructure rebates and government investments, and removal of any barriers to adoption of clean technologies. Consider removal of any policies that directly or indirectly favor transportation using privately owned vehicles (e.g., parking subsidies) and production/consumption of fossil fuels (e.g., tax credits, loan forgiveness, accelerated depreciation). If possible, also consider changes in infrastructure and urban redesign to encourage mobility options (e.g., reducing parking lots and parking spaces to optimize for pedestrians/cyclists/micromobility). To the extent possible, consider any other futuristic scenario that could significantly alter future transportation systems to improve efficiency (e.g., use of drones for all urban delivery, proliferation of 3-D printing to reduce shipping demand).
- **Behavioral Changes:**
  - Aggressive: Remove behavioral/preference barriers to clean energy adoption (e.g., penalties or costs associated with range anxiety, lack of refueling options). Consider any reasonable change in parameters that favors emissions reductions (as captured in your model) but do not limit travel demand exogenously. For example, allow for increased vehicle occupancy or "right-sizing", preference for lower energy modes (e.g., walking, micromobility), preference for smaller vehicles, reduction in privately vehicle ownership, and preference for car sharing and ride sharing.

Appendix D

Carbon Management Study Group



EMF 37 Core scenario matrix—14 scenarios

Core Scenarios				
Policy Technology	No target	Net 0 in 2050	Net 0 in 2060	Net 0 in 2080
Ref technology	1	2	3	4
Adv. All End-use Sectors	5	6	7	8
Adv. Elec Transport	9	10		
Adv. Elec Buildings	11	12		
Adv. Elec Industry	13	14		

DRAFT PRESENTATION—DO NOT QUOTE, SUBJECT TO CHANGE 5

CMSG Scenarios

EMF37 Core and Carbon Management Study Group (CMSG) Scenarios

	Technology				Net Zero Year		
Scenario ↓	CCS	H2 production and use	DAC	BAU	2050	2060	2080
EMF37 Reference	Ref	Ref	Ref	EMF37-01	EMF37-02	EMF37-03	EMF37-04
CMSG-1	None	Ref	None		CMSG-01-2050	CMSG-01-2060	CMSG-01-2080
CMSG-2	Adv	Ref	Ref		CMSG-02-2050	CMSG-02-2060	CMSG-02-2080
CMSG-3	Ref	Adv	Ref		CMSG-03-2050	CMSG-03-2060	CMSG-03-2080
CMSG-4	Ref	Ref	Adv		CMSG-04-2050	CMSG-04-2060	CMSG-04-2080
CMSG-5	Adv	Adv	Adv	CMSG-03-BAU	CMSG-05-2050	CMSG-05-2060	CMSG-05-2080

Priority Order
Priority 1
Priority 2
Priority 3
Priority 4

Principal focus of the EMF 37 Core study is net zero in 2050

DRAFT PRESENTATION—DO NOT QUOTE, SUBJECT TO CHANGE

CMSG Scenarios

EMF37 Core and Carbon Manageme udy Group (CMSG) Scenarios

1

	Technology				Net Zero Year		
Scenario ↓	CCS	H2 production and use	DAC	BAU	2050	2060	2080
EMF37 Reference	Ref	Ref	Ref	EMF37-01	EMF37-02	EMF37-03	EMF37-04
CMSG-1	None	Ref	None		CMSG-01-2050	CMSG-01-2060	CMSG-01-2080
CMSG-2	Adv	Ref	Ref		CMSG-02-2050	CMSG-02-2060	CMSG-02-2080
CMSG-3	Ref	Adv	Ref		CMSG-03-2050	CMSG-03-2060	CMSG-03-2080
CMSG-4	Ref	Ref	Adv		CMSG-04-2050	CMSG-04-2060	CMSG-04-2080
CMSG-5	Adv	Adv	Adv	C -BAU	CMSG-05-2050	CMSG-05-2060	CMSG-05-2080

Priority Order
Priority 1
Priority 2
Priority 3
Priority 4

Our 1st scenario is a core scenario, EMF37-01
- No Target
- BAU tech, pop, GDP

DRAFT PRESENTATION—COMMENTS WELCOME

DRAFT PRESENTATION—DO NOT QUOTE, SUBJECT TO CHANGE

CMSG Scenarios

EMF37 Core and Carbon Management Study Group (CMSG) Scenarios

2

	Technology				Ne r		
Scenario ↓	CCS	H2 production and use	DAC	BAU	2050		2080
EMF37 Reference	Ref	Ref	Ref	EMF37-01	EMF37-02	EMF37-03	EMF37-04
CMSG-1	None	Ref	None		CMSG-01-2050	CMS 0	CMSG-01-2080
CMSG-2	Adv	Ref	Ref		CMSG-02-2050	CMSG	CMSG-02-2080
CMSG-3	Ref	Adv	Ref		CMSG-03-2050	CM 60	CMSG-03-2080
C					050	C 2060	CMSG-04-2080
C					050	5-2060	CMSG-05-2080

Priority Order
Priority 1
Priority 2
Priority 3
Priority 4

Our 2nd scenario is a CMSG scenario—CMSG-01-2080
- Policies (default carbon tax) to deliver reductions in emissions to 50% of 2020 in 2050
- **CCS AVAILABLE** + default H2 and DAC assumptions
- For energy-economy models—terrestrial systems
  - -800 MMTCO2/year
  - Bioenergy—borrow assumptions from other models

DRAFT PRESENTATION—DO NOT QUOTE, SUBJECT TO CHANGE

CMSG Scenarios

EMF37 Core and Carbon Management Study Group (CMSG) Scenarios

Scenario ↓	Technology: CCS	Technology: H2 production and use	Technology: DAC	BAU	Net Zero Year: 2050	Net Zero Year: 2060	Net Zero Year: 2080	Priority Order
EMF37 Reference	Ref	Ref	Ref	EMF37-01	EMF37-02	EMF37-03	EMF37-04	Priority 1
CMSG-1	None	Ref	None		CMSG-01-2050	CMSG-01-206[illegible]	CMSG-01-2080	Priority 2
CMSG-2	Adv	Ref	Ref		CMSG-02-2050	CMSG-[illegible]	CMSG-02-2080	Priority 3
CMSG-3	Ref	Adv	Ref		CMSG-03-2050	[illegible]	CMSG-03-2080	Priority 4
CMSG-4	Ref	Ref	Adv		CMSG-04-2050	[illegible]	CMSG-04-2080	
CMSG-5	Adv	Adv	Adv	[illegible]-BAU	CMSG-05-[illegible]	[illegible]-05-2060	CMSG-05-2080	

Our focus is on learning in stages
Stage 1—solve for Ref + Net Zero 2080

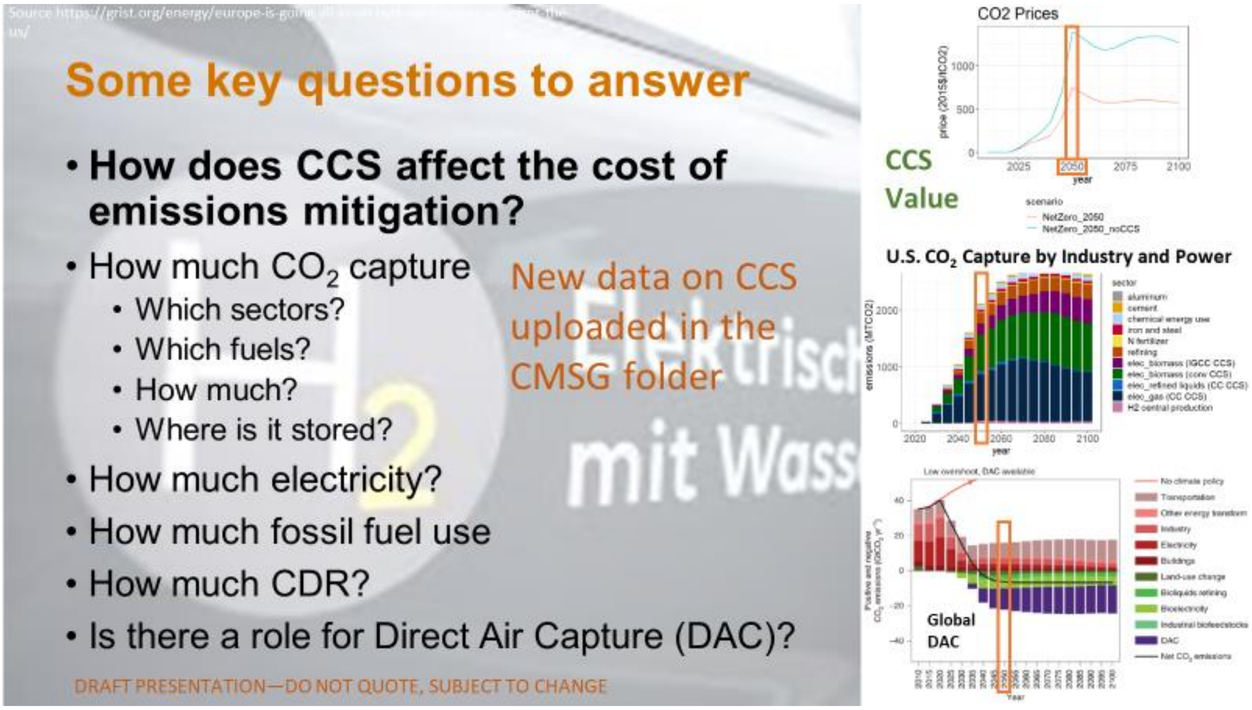
CMSG Met Friday 07 May 2021 to discuss progress and direction

EMF37 Core and Carbon Management Study Group (CMSG) Scenarios

Scenario ↓	Technology: CCS	Technology: H2 production and use	Technology: DAC	BAU	Net Zero Year: 2050	Net Zero Year: 2060	Net Zero Year: 2080	Priority Order
EMF37 Reference	Ref	Ref	Ref	EMF37-01	EMF37-02	EMF37-03	EMF37-04	Priority 1
CMSG-1	None	Ref	None		CMSG-01-2050	[illegible]MSG-01-2060	CMSG-01-2080	Priority 2
CMSG-2	Adv	Ref	Ref		[illegible]	CMSG-02-2060	CMSG-02-2080	Priority 3
CMSG-3	Ref	Adv	Ref		[illegible]MSG-03-2050	CMSG-03-2060	CMSG-03-2080	Priority 4
CMSG-4	Ref	Ref	Adv		[illegible]MSG-04-2050	CMSG-04-2060	CMSG-04-2080	
CMSG-5	Adv	Adv	Adv	CM[illegible]	CMSG-05-2050	CMSG-05-2060	CMSG-05-2080	

After our discussion last week, we discussed running 3 NetZero 2050 scenarios, if possible.

DRAFT PRESENTATION—DO NOT QUOTE, SUBJECT TO CHANGE


Some key questions to answer
• How does CCS affect the cost of emissions mitigation?
• How much CO2 capture
• Which sectors?
• Which fuels?
• How much?
• Where is it stored?
• How much electricity?
• How much fossil fuel use
• How much CDR?
• Is there a role for Direct Air Capture (DAC)?
New data on CCS uploaded in the CMSG folder
DRAFT PRESENTATION—DO NOT QUOTE, SUBJECT TO CHANGE
CO2 Prices
price (2015$/tCO2)
year
CCS Value
scenario
NetZero_2050
NetZero_2050_noCCS
U.S. CO2 Capture by Industry and Power
emissions (MTCO2)
sector
aluminum
cement
chemical energy use
iron and steel
N fertilizer
refining
elec_biomass (IGCC CCS)
elec_biomass (conv CCS)
elec_refined liquids (CC CCS)
elec_gas (CC CCS)
H2 central production
Low overshoot, DAC available
No climate policy
Transportation
Other energy transform
Industry
Electricity
Buildings
Land-use change
Bioliquids refining
Bioelectricity
Industrial biofeedstocks
DAC
Net CO2 emissions
Global DAC
Year

Appendix E

EMF 37 Round#1 Final Data Template

(for variable definitions see https://docs.google.com/spreadsheets/d/1n5KA5aBNfZRXDskfkt4WwDVGTEALlmk6/edit#gid=385390163)

Round	Category	Tier	Variable	Unit
1	CCS	1	Carbon Sequestration|CCS	Mt CO2/yr
1	CCS	1	Carbon Sequestration|CCS|Biomass|Energy	Mt CO2/yr
1	CCS	1	Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry|EInt Mfg	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry|EInt Mfg|Aluminum	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry|EInt Mfg|Bulk chemicals	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry|EInt Mfg|Cement and Lime	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry|EInt Mfg|Food products	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry|EInt Mfg|Glass	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry|EInt Mfg|Iron and steel	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry|EInt Mfg|Other	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry|EInt Mfg|Paper	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry|Non Mfg	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Supply|Biogas	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Supply|Biomass Liquids	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Supply|Biomass Solids	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Supply|Electricity	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Biomass|Energy|Supply|Electricity|New Builds	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Biomass|Energy|Supply|Electricity|Retrofit	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Supply|Heat	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Supply|Hydrogen	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Supply|Petroleum Refining	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Supply|Synthetic Gas	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Biomass|Energy|Supply|Synthetic Liquids	Mt CO2/yr
1	CCS	1	Carbon Sequestration|CCS|Biomass|Industrial Processes	Mt CO2/yr

1	CCS	3	Carbon Sequestration|CCS|Biomass|Industrial Processes|EInt Mfg	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Biomass|Industrial Processes|EInt Mfg|Aluminum	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Biomass|Industrial Processes|EInt Mfg|Bulk chemicals	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Biomass|Industrial Processes|EInt Mfg|Cement and Lime	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Biomass|Industrial Processes|EInt Mfg|Food products	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Biomass|Industrial Processes|EInt Mfg|Glass	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Biomass|Industrial Processes|EInt Mfg|Iron and steel	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Biomass|Industrial Processes|EInt Mfg|Other	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Biomass|Industrial Processes|EInt Mfg|Paper	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Enhanced Weathering	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy	Mt CO2/yr
1	CCS	1	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry|EInt Mfg	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry|EInt Mfg|Aluminum	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry|EInt Mfg|Bulk chemicals	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry|EInt Mfg|Cement and Lime	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry|EInt Mfg|Food products	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry|EInt Mfg|Glass	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry|EInt Mfg|Iron and steel	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry|EInt Mfg|Other	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry|EInt Mfg|Paper	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry|Non Mfg	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Supply	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Supply|Biogas	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Supply|Biomass Liquids	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Supply|Biomass Solids	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Supply|Electricity	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Fossil|Energy|Supply|Electricity|New Builds	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Fossil|Energy|Supply|Electricity|Retrofit	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Supply|Heat	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Supply|Hydrogen	Mt CO2/yr

1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Supply|Petroleum Refining	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Supply|Synthetic Gas	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Fossil|Energy|Supply|Synthetic Liquids	Mt CO2/yr
1	CCS	2	Carbon Sequestration|CCS|Non-Biomass|Industrial Processes	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Non-Biomass|Industrial Processes|EInt Mfg	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Non-Biomass|Industrial Processes|EInt Mfg|Aluminum	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Non-Biomass|Industrial Processes|EInt Mfg|Bulk chemicals	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Non-Biomass|Industrial Processes|EInt Mfg|Cement and Lime	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Non-Biomass|Industrial Processes|EInt Mfg|Food products	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Non-Biomass|Industrial Processes|EInt Mfg|Glass	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Non-Biomass|Industrial Processes|EInt Mfg|Iron and steel	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Non-Biomass|Industrial Processes|EInt Mfg|Other	Mt CO2/yr
1	CCS	3	Carbon Sequestration|CCS|Non-Biomass|Industrial Processes|EInt Mfg|Paper	Mt CO2/yr
1	CCS	2	Carbon Sequestration|Chemical Feedstocks	Mt CO2/yr
1	CCS	1	Carbon Sequestration|Chemical Feedstocks|Biomass	Mt CO2/yr
1	CCS	3	Carbon Sequestration|Chemical Feedstocks|Fossil	Mt CO2/yr
1	CCS	1	Carbon Sequestration|Direct Air Capture|Net	Mt CO2/yr
1	CCS	1	Carbon Sequestration|Direct Air Capture|Total	Mt CO2/yr
1	CCS	1	Carbon Sequestration|LULUCF	Mt CO2/yr
1	CCS	3	Carbon Sequestration|LULUCF|Afforestation	Mt CO2/yr
1	CCS	3	Carbon Sequestration|LULUCF|Biochar	Mt CO2/yr
1	CCS	3	Carbon Sequestration|LULUCF|Other	Mt CO2/yr
1	CCS	3	Carbon Sequestration|LULUCF|Soil Carbon Management	Mt CO2/yr
1	CCS	3	Carbon Sequestration|Other	Mt CO2/yr
1	CCS	3	Carbon Utilization|CCS|Synthetic Gas	Mt CO2/yr
1	CCS	3	Carbon Utilization|CCS|Synthetic Liquid	Mt CO2/yr
1	CCS	1	CO2 storage	Mt CO2/yr
1	CCS	3	CO2 storage|Basalt	Mt CO2/yr
1	CCS	3	CO2 storage|Coal Seams	Mt CO2/yr
1	CCS	3	CO2 storage|EOR	Mt CO2/yr
1	CCS	3	CO2 storage|Other mineralization	Mt CO2/yr
1	CCS	3	CO2 storage|Saline Off Shore	Mt CO2/yr
1	CCS	3	CO2 storage|Saline On Shore	Mt CO2/yr
1	Costs	3	Cost|Capital|CO2 Capture|Electricity|Biomass|New	US$2018/kW
1	Costs	3	Cost|Capital|CO2 Capture|Electricity|Biomass|Retrofit	US$2018/kW

1	Costs	3	Cost|Capital|CO2 Capture|Electricity|Coal|New	US$2018/kW
1	Costs	3	Cost|Capital|CO2 Capture|Electricity|Coal|Retrofit	US$2018/kW
1	Costs	3	Cost|Capital|CO2 Capture|Electricity|Gas|New	US$2018/kW
1	Costs	3	Cost|Capital|CO2 Capture|Electricity|Gas|Retrofit	US$2018/kW
1	Costs	3	Cost|Capital|CO2 Capture|Electricity|Oil|New	US$2018/kW
1	Costs	3	Cost|Capital|CO2 Capture|Electricity|Oil|Retrofit	US$2018/kW
1	Costs	3	Cost|Capital|CO2 Capture|H2 Production|Chemical	US$2018/EJ of products
1	Costs	3	Cost|Capital|CO2 Capture|H2 Production|Electrolysis	US$2018/EJ of products
1	Costs	3	Cost|Capital|CO2 Capture|H2 Production|Thermal	US$2018/EJ of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Aluminum|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Aluminum|Coal	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Aluminum|Gas	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Aluminum|Oil	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Coal	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Gas	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Oil	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Cement and lime|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Cement and lime|Coal	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Cement and lime|Gas	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Cement and lime|Oil	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Food products|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Food products|Coal	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Food products|Gas	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Food products|Oil	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Glass|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Glass|Coal	US$2018/Mt of products

1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Glass|Gas	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Glass|Oil	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Iron and steel|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Iron and steel|Coal	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Iron and steel|Gas	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Iron and steel|Oil	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Other|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Other|Coal	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Other|Gas	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Other|Oil	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Paper|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Paper|Coal	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Paper|Gas	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Paper|Oil	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Refineries|Biomass	US$2018/EJ of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Refineries|Coal	US$2018/EJ of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Refineries|Gas	US$2018/EJ of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|EInt Mfg|Refineries|Oil	US$2018/EJ of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|Non Mfg|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|Non Mfg|Coal	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|Non Mfg|Gas	US$2018/Mt of products
1	Costs	3	Cost|Capital|CO2 Capture|Industry|Non Mfg|Oil	US$2018/Mt of products
1	Costs	4	Cost|Capital|Electricity|Biomass|w/ CCS	US$2018/kW
1	Costs	4	Cost|Capital|Electricity|Biomass|w/o CCS	US$2018/kW
1	Costs	4	Cost|Capital|Electricity|Coal|w/ CCS	US$2018/kW
1	Costs	4	Cost|Capital|Electricity|Coal|w/o CCS	US$2018/kW
1	Costs	4	Cost|Capital|Electricity|Gas|w/ CCS	US$2018/kW

1	Costs	4	Cost|Capital|Electricity|Gas|w/o CCS	US$2018/kW
1	Costs	4	Cost|Capital|Electricity|Geothermal	US$2018/kW
1	Costs	4	Cost|Capital|Electricity|Hydro	US$2018/kW
1	Costs	4	Cost|Capital|Electricity|Nuclear	US$2018/kW
1	Costs	4	Cost|Capital|Electricity|Solar|CSP	US$2018/kW
1	Costs	4	Cost|Capital|Electricity|Solar|PV	US$2018/kW
1	Costs	4	Cost|Capital|Electricity|Wind|Offshore	US$2018/kW
1	Costs	4	Cost|Capital|Electricity|Wind|Onshore	US$2018/kW
1	Costs	4	Cost|Capital|Gases|Biomass|w/ CCS	US$2018/kW
1	Costs	4	Cost|Capital|Gases|Biomass|w/o CCS	US$2018/kW
1	Costs	4	Cost|Capital|Gases|Coal|w/ CCS	US$2018/kW
1	Costs	4	Cost|Capital|Gases|Coal|w/o CCS	US$2018/kW
1	Costs	4	Cost|Capital|Hydrogen|Biomass|w/ CCS	US$2018/kW
1	Costs	4	Cost|Capital|Hydrogen|Biomass|w/o CCS	US$2018/kW
1	Costs	4	Cost|Capital|Hydrogen|Coal|w/ CCS	US$2018/kW
1	Costs	4	Cost|Capital|Hydrogen|Coal|w/o CCS	US$2018/kW
1	Costs	4	Cost|Capital|Hydrogen|Electricity	US$2018/kW
1	Costs	4	Cost|Capital|Hydrogen|Gas|w/ CCS	US$2018/kW
1	Costs	4	Cost|Capital|Hydrogen|Gas|w/o CCS	US$2018/kW
1	Costs	4	Cost|Capital|Liquids|Biomass|w/ CCS	US$2018/kW
1	Costs	4	Cost|Capital|Liquids|Biomass|w/o CCS	US$2018/kW
1	Costs	4	Cost|Capital|Liquids|Coal|w/ CCS	US$2018/kW
1	Costs	4	Cost|Capital|Liquids|Coal|w/o CCS	US$2018/kW
1	Costs	4	Cost|Capital|Liquids|Gas|w/ CCS	US$2018/kW
1	Costs	4	Cost|Capital|Liquids|Gas|w/o CCS	US$2018/kW
1	Costs	4	Cost|Capital|Liquids|Oil	US$2018/kW
1	Costs	3	Cost|Carbon Capture|Transport and Storage	US$2018/t CO2

1	Costs	3	Cost|Fixed O&M|CO2 Capture|Electricity|Biomass|New	US$2018/kW
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Electricity|Biomass|Retrofit	US$2018/kW
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Electricity|Coal|New	US$2018/kW
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Electricity|Coal|Retrofit	US$2018/kW
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Electricity|Gas|New	US$2018/kW
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Electricity|Gas|Retrofit	US$2018/kW
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Electricity|Oil|New	US$2018/kW
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Electricity|Oil|Retrofit	US$2018/kW
1	Costs	3	Cost|Fixed O&M|CO2 Capture|H2 Production|Chemical	US$2018/EJ of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|H2 Production|Electrolysis	US$2018/EJ of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|H2 Production|Thermal	US$2018/EJ of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Aluminum|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Aluminum|Coal	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Aluminum|Gas	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Aluminum|Oil	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Coal	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Gas	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Oil	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Cement and lime|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Cement and lime|Coal	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Cement and lime|Gas	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Cement and lime|Oil	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Food products|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Food products|Coal	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Food products|Gas	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Food products|Oil	US$2018/Mt of products

1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Glass|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Glass|Coal	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Glass|Gas	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Glass|Oil	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Iron and steel|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Iron and steel|Coal	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Iron and steel|Gas	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Iron and steel|Oil	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Other|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Other|Coal	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Other|Gas	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Other|Oil	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Paper|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Paper|Coal	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Paper|Gas	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Paper|Oil	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Refineries|Biomass	US$2018/EJ of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Refineries|Coal	US$2018/EJ of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Refineries|Gas	US$2018/EJ of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|EInt Mfg|Refineries|Oil	US$2018/EJ of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|Non Mfg|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|Non Mfg|Coal	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|Non Mfg|Gas	US$2018/Mt of products
1	Costs	3	Cost|Fixed O&M|CO2 Capture|Industry|Non Mfg|Oil	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Electricity|Biomass|New	US$2018/kW
1	Costs	3	Cost|Variable O&M|CO2 Capture|Electricity|Biomass|Retrofit	US$2018/kW
1	Costs	3	Cost|Variable O&M|CO2 Capture|Electricity|Coal|New	US$2018/kW

1	Costs	3	Cost|Variable O&M|CO2 Capture|Electricity|Coal|Retrofit	US$2018/kW
1	Costs	3	Cost|Variable O&M|CO2 Capture|Electricity|Gas|New	US$2018/kW
1	Costs	3	Cost|Variable O&M|CO2 Capture|Electricity|Gas|Retrofit	US$2018/kW
1	Costs	3	Cost|Variable O&M|CO2 Capture|Electricity|Oil|New	US$2018/kW
1	Costs	3	Cost|Variable O&M|CO2 Capture|Electricity|Oil|Retrofit	US$2018/kW
1	Costs	3	Cost|Variable O&M|CO2 Capture|H2 Production|Chemical	US$2018/EJ of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|H2 Production|Electrolysis	US$2018/EJ of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|H2 Production|Thermal	US$2018/EJ of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Aluminum|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Aluminum|Coal	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Aluminum|Gas	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Aluminum|Oil	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Coal	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Gas	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Bulk chemicals|Oil	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Cement and lime|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Cement and lime|Coal	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Cement and lime|Gas	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Cement and lime|Oil	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Food products|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Food products|Coal	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Food products|Gas	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Food products|Oil	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Glass|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Glass|Coal	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Glass|Gas	US$2018/Mt of products

1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Glass|Oil	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Iron and steel|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Iron and steel|Coal	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Iron and steel|Gas	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Iron and steel|Oil	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Other|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Other|Coal	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Other|Gas	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Other|Oil	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Paper|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Paper|Coal	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Paper|Gas	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Paper|Oil	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Refineries|Biomass	US$2018/EJ of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Refineries|Coal	US$2018/EJ of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Refineries|Gas	US$2018/EJ of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|EInt Mfg|Refineries|Oil	US$2018/EJ of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|Non Mfg|Biomass	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|Non Mfg|Coal	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|Non Mfg|Gas	US$2018/Mt of products
1	Costs	3	Cost|Variable O&M|CO2 Capture|Industry|Non Mfg|Oil	US$2018/Mt of products
1	Demography	1	Population	Million
1	Economy	2	Consumption|Electricity|Quintile 1	billion US$2018/yr
1	Economy	2	Consumption|Electricity|Quintile 2	billion US$2018/yr
1	Economy	2	Consumption|Electricity|Quintile 3	billion US$2018/yr
1	Economy	2	Consumption|Electricity|Quintile 4	billion US$2018/yr
1	Economy	2	Consumption|Electricity|Quintile 5	billion US$2018/yr

1	Economy	2	Consumption|Energy|Quintile 1	billion US$2018/yr
1	Economy	2	Consumption|Energy|Quintile 2	billion US$2018/yr
1	Economy	2	Consumption|Energy|Quintile 3	billion US$2018/yr
1	Economy	2	Consumption|Energy|Quintile 4	billion US$2018/yr
1	Economy	2	Consumption|Energy|Quintile 5	billion US$2018/yr
1	Economy	2	Consumption|Total|Quintile 1	billion US$2018/yr
1	Economy	2	Consumption|Total|Quintile 2	billion US$2018/yr
1	Economy	2	Consumption|Total|Quintile 3	billion US$2018/yr
1	Economy	2	Consumption|Total|Quintile 4	billion US$2018/yr
1	Economy	2	Consumption|Total|Quintile 5	billion US$2018/yr
1	Economy	1	GDP|Consumption	billion US$2018/yr
1	Economy	1	GDP|Exports	billion US$2018/yr
1	Economy	1	GDP|Government	billion US$2018/yr
1	Economy	1	GDP|Imports	billion US$2018/yr
1	Economy	1	GDP|Investment	billion US$2018/yr
1	Economy	1	GDP|MER	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Aluminum|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Aluminum|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Bulk chemicals|Inorganic|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Bulk chemicals|Inorganic|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Bulk chemicals|Organic|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Bulk chemicals|Organic|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Bulk chemicals|Resins|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Bulk chemicals|Resins|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Bulk chemicals|Value	billion US$2018/yr

1	Economy	3	Output|Industry|EInt Mfg|Bulk chemicals|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Cement and lime|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Cement and lime|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Food products|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Food products|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Glass|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Glass|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Iron and steel|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Iron and steel|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Other|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Other|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Paper|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Paper|Volume	Index 2020=1
1	Economy	3	Output|Industry|EInt Mfg|Refineries|Value	billion US$2018/yr
1	Economy	3	Output|Industry|EInt Mfg|Refineries|Volume	Index 2020=1
1	Economy	2	Output|Industry|EInt Mfg|Value	billion US$2018/yr
1	Economy	2	Output|Industry|EInt Mfg|Volume	Index 2020=1
1	Economy	3	Output|Industry|Non Mfg|Agriculture|Crops|Value	billion US$2018/yr
1	Economy	3	Output|Industry|Non Mfg|Agriculture|Crops|Volume	Index 2020=1
1	Economy	3	Output|Industry|Non Mfg|Agriculture|Forestry|Value	billion US$2018/yr
1	Economy	3	Output|Industry|Non Mfg|Agriculture|Forestry|Volume	Index 2020=1
1	Economy	3	Output|Industry|Non Mfg|Agriculture|Other|Value	billion US$2018/yr
1	Economy	3	Output|Industry|Non Mfg|Agriculture|Other|Volume	Index 2020=1
1	Economy	3	Output|Industry|Non Mfg|Agriculture|Value	billion US$2018/yr
1	Economy	3	Output|Industry|Non Mfg|Agriculture|Volume	Index 2020=1
1	Economy	3	Output|Industry|Non Mfg|Coal mining|Value	billion US$2018/yr
1	Economy	3	Output|Industry|Non Mfg|Coal mining|Volume	Index 2020=1

1	Economy	3	Output|Industry|Non Mfg|Construction|Value	billion US$2018/yr
1	Economy	3	Output|Industry|Non Mfg|Construction|Volume	Index 2020=1
1	Economy	3	Output|Industry|Non Mfg|Government|Value	billion US$2018/yr
1	Economy	3	Output|Industry|Non Mfg|Government|Volume	Index 2020=1
1	Economy	3	Output|Industry|Non Mfg|Oil-gas extraction|Value	billion US$2018/yr
1	Economy	3	Output|Industry|Non Mfg|Oil-gas extraction|Volume	Index 2020=1
1	Economy	3	Output|Industry|Non Mfg|Other mining|Value	billion US$2018/yr
1	Economy	3	Output|Industry|Non Mfg|Other mining|Volume	Index 2020=1
1	Economy	3	Output|Industry|Non Mfg|Other|Value	billion US$2018/yr
1	Economy	3	Output|Industry|Non Mfg|Other|Volume	Index 2020=1
1	Economy	3	Output|Industry|Non Mfg|Services|Value	billion US$2018/yr
1	Economy	3	Output|Industry|Non Mfg|Services|Volume	Index 2020=1
1	Economy	2	Output|Industry|Non Mfg|Value	billion US$2018/yr
1	Economy	2	Output|Industry|Non Mfg|Volume	Index 2020=1
1	Economy	3	Output|Industry|NonEInt Mfg|Balance of manufacturing|Value	billion US$2018/yr
1	Economy	3	Output|Industry|NonEInt Mfg|Balance of manufacturing|Volume	Index 2020=1
1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Appliances|Value	billion US$2018/yr
1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Appliances|Volume	Index 2020=1
1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Computer|Value	billion US$2018/yr
1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Computer|Volume	Index 2020=1
1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Fab metal|Value	billion US$2018/yr
1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Fab metal|Volume	Index 2020=1
1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Machinery|Value	billion US$2018/yr
1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Machinery|Volume	Index 2020=1
1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Transport equip|Value	billion US$2018/yr
1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Transport equip|Volume	Index 2020=1
1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Value	billion US$2018/yr

1	Economy	3	Output|Industry|NonEInt Mfg|Metal durables|Volume	Index 2020=1
1	Economy	3	Output|Industry|NonEInt Mfg|Plastic & rubber|Value	billion US$2018/yr
1	Economy	3	Output|Industry|NonEInt Mfg|Plastic & rubber|Volume	Index 2020=1
1	Economy	2	Output|Industry|NonEInt Mfg|Value	billion US$2018/yr
1	Economy	2	Output|Industry|NonEInt Mfg|Volume	Index 2020=1
1	Economy	3	Output|Industry|NonEInt Mfg|Wood Products|Value	billion US$2018/yr
1	Economy	3	Output|Industry|NonEInt Mfg|Wood Products|Volume	Index 2020=1
1	Economy	1	Output|Industry|Value	billion US$2018/yr
1	Economy	1	Output|Industry|Volume	Index 2020=1
1	Economy	1	Price|Final Energy|Biogas	US$2018/GJ
1	Economy	1	Price|Final Energy|Biomass Liquids	US$2018/GJ
1	Economy	1	Price|Final Energy|Biomass Solids	US$2018/GJ
1	Economy	2	Price|Final Energy|Commercial|Biogas	US$2018/GJ
1	Economy	2	Price|Final Energy|Commercial|Biomass Liquids	US$2018/GJ
1	Economy	2	Price|Final Energy|Commercial|Electricity	US$2018/GJ
1	Economy	2	Price|Final Energy|Commercial|Gas	US$2018/GJ
1	Economy	2	Price|Final Energy|Commercial|Hydrogen	US$2018/GJ
1	Economy	2	Price|Final Energy|Commercial|Oil	US$2018/GJ
1	Economy	2	Price|Final Energy|Commercial|Synthetic Gas	US$2018/GJ
1	Economy	2	Price|Final Energy|Commercial|Synthetic Liquids	US$2018/GJ
1	Economy	1	Price|Final Energy|Electricity	US$2018/GJ
1	Economy	1	Price|Final Energy|Gas	US$2018/GJ
1	Economy	1	Price|Final Energy|Gas-Hydrogen blend	US$2018/GJ
1	Economy	1	Price|Final Energy|Hydrogen	US$2018/GJ
1	Economy	2	Price|Final Energy|Industrial|Biogas	US$2018/GJ
1	Economy	2	Price|Final Energy|Industrial|Biomass Liquids	US$2018/GJ
1	Economy	2	Price|Final Energy|Industrial|Electricity	US$2018/GJ
1	Economy	2	Price|Final Energy|Industrial|Gas	US$2018/GJ
1	Economy	2	Price|Final Energy|Industrial|Hydrogen	US$2018/GJ
1	Economy	2	Price|Final Energy|Industrial|Oil	US$2018/GJ
1	Economy	2	Price|Final Energy|Industrial|Synthetic Gas	US$2018/GJ
1	Economy	2	Price|Final Energy|Industrial|Synthetic Liquids	US$2018/GJ
1	Economy	1	Price|Final Energy|Oil	US$2018/GJ
1	Economy	2	Price|Final Energy|Residential|Biogas	US$2018/GJ
1	Economy	2	Price|Final Energy|Residential|Biomass Liquids	US$2018/GJ
1	Economy	2	Price|Final Energy|Residential|Electricity	US$2018/GJ
1	Economy	2	Price|Final Energy|Residential|Gas	US$2018/GJ

1	Economy	2	Price|Final Energy|Residential|Hydrogen	US$2018/GJ
1	Economy	2	Price|Final Energy|Residential|Oil	US$2018/GJ
1	Economy	2	Price|Final Energy|Residential|Synthetic Gas	US$2018/GJ
1	Economy	2	Price|Final Energy|Residential|Synthetic Liquids	US$2018/GJ
1	Economy	1	Price|Final Energy|Synthetic Gas	US$2018/GJ
1	Economy	1	Price|Final Energy|Synthetic Liquids	US$2018/GJ
1	Economy	2	Price|Final Energy|Transportation|Biogas	US$2018/GJ
1	Economy	2	Price|Final Energy|Transportation|Biomass Liquids	US$2018/GJ
1	Economy	2	Price|Final Energy|Transportation|Electricity	US$2018/GJ
1	Economy	2	Price|Final Energy|Transportation|Gas	US$2018/GJ
1	Economy	2	Price|Final Energy|Transportation|Hydrogen	US$2018/GJ
1	Economy	2	Price|Final Energy|Transportation|Oil|Diesel	US$2018/GJ
1	Economy	2	Price|Final Energy|Transportation|Oil|Gasoline	US$2018/GJ
1	Economy	2	Price|Final Energy|Transportation|Oil|Jet Fuel	US$2018/GJ
1	Economy	2	Price|Final Energy|Transportation|Synthetic Gas	US$2018/GJ
1	Economy	2	Price|Final Energy|Transportation|Synthetic Liquids	US$2018/GJ
1	Economy	1	Price|Primary Energy|Biomass	US$2018/GJ
1	Economy	1	Price|Primary Energy|Coal	US$2018/GJ
1	Economy	1	Price|Primary Energy|Gas	US$2018/GJ
1	Economy	1	Price|Primary Energy|Oil	US$2018/GJ
1	Economy	3	Trade|Terms	Index
1	Economy	1	Welfare	%
1	Emissions	3	Emissions|BC	Mt BC/yr
1	Emissions	2	Emissions|CH4	Mt CH4/yr
1	Emissions	3	Emissions|CH4|AFOLU	Mt CH4/yr
1	Emissions	3	Emissions|CH4|Energy	Mt CH4/yr
1	Emissions	3	Emissions|CH4|Other	Mt CH4/yr
1	Emissions	3	Emissions|CO	Mt CO/yr
1	Emissions	2	Emissions|CO2	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Coal	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Demand|Buildings	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Energy|Demand|Buildings|Commercial	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Commercial|Appliances	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Commercial|Appliances|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Commercial|Cooling	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Commercial|Cooling|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Commercial|Heating	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Commercial|Heating|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Commercial|Indirect	Mt CO2/yr

1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Commercial|Lighting	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Commercial|Lighting|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Commercial|Other	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Commercial|Other|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Indirect	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Energy|Demand|Buildings|Residential	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Residential|Appliances	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Residential|Appliances|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Residential|Cooling	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Residential|Cooling|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Residential|Heating	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Residential|Heating|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Residential|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Residential|Lighting	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Residential|Lighting|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Residential|Other	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Buildings|Residential|Other|Indirect	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Demand|Industry	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Energy|Demand|Industry|EInt Mfg	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Aluminum	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Aluminum|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Bulk chemicals	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Bulk chemicals|Ag chemicals	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Bulk chemicals|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Bulk chemicals|Inorganic	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Bulk chemicals|Inorganic|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Bulk chemicals|Organic	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Bulk chemicals|Organic|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Bulk chemicals|Resins	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Bulk chemicals|Resins|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Cement and lime	Mt CO2/yr

1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Cement and lime|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Food products	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Food products|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Glass	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Glass|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Iron and steel	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Iron and steel|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Other	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Other|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Paper	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Paper|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|EInt Mfg|Refineries|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Indirect	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Energy|Demand|Industry|Non Mfg	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Agriculture	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Agriculture|Crops	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Agriculture|Crops|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Agriculture|Forestry	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Agriculture|Forestry|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Agriculture|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Agriculture|Other	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Agriculture|Other|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Coal mining	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Coal mining|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Construction	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Construction|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Oil-gas extraction	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Oil-gas extraction|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Other	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Other mining	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Other mining|Indirect	Mt CO2/yr

1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|Non Mfg|Other|Indirect	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Balance of manufacturing	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Balance of manufacturing|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables|Appliances	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables|Appliances|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables|Computer	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables|Computer|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables|Fab metal	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables|Fab metal|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables|Machinery	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables|Machinery|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables|Transport equip	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Metal durables|Transport equip|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Plastic & rubber	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Plastic & rubber|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Wood Products	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Industry|NonEInt Mfg|Wood Products|Indirect	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Demand|Transportation	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Energy|Demand|Transportation|Freight	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Freight|Aviation	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Freight|Aviation|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Freight|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Freight|Rail	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Freight|Rail|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Freight|Road	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Freight|Road|Indirect	Mt CO2/yr

1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Freight|Shipping|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Indirect	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Energy|Demand|Transportation|Offroad	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Offroad|Indirect	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Energy|Demand|Transportation|Passenger	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Passenger|Aviation	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Passenger|Aviation|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Passenger|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Passenger|Other	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Passenger|Other|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Passenger|Rail	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Passenger|Rail|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Passenger|Road	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Passenger|Road|Indirect	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Energy|Demand|Transportation|Passenger|Shipping	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Energy|Demand|Transportation|Pipeline	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Gas	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Oil	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Biogas	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Biomass Liquids	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Electricity	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Electricity|Biomass	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Electricity|Coal	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Electricity|Gas	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Electricity|Oil	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Heat	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Hydrogen	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Petroleum Refining	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Synthetic Gas	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Energy|Supply|Synthetic Liquids	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Industrial Processes	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Industrial Processes|EInt Mfg|Aluminum	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Industrial Processes|EInt Mfg|Bulk chemicals	Mt CO2/yr
1	Emissions	3	Emissions|CO2|Industrial Processes|EInt Mfg|Bulk chemicals|Agricultural chemicals	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Industrial Processes|EInt Mfg|Cement and Lime	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Industrial Processes|EInt Mfg|Food products	Mt CO2/yr

1	Emissions	2	Emissions|CO2|Industrial Processes|EInt Mfg|Glass	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Industrial Processes|EInt Mfg|Iron and steel	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Industrial Processes|EInt Mfg|Other	Mt CO2/yr
1	Emissions	2	Emissions|CO2|Industrial Processes|EInt Mfg|Paper	Mt CO2/yr
1	Emissions	1	Emissions|CO2|Other	Mt CO2/yr
1	Emissions	2	Emissions|F-Gases	Mt CO2-equiv/yr
1	Emissions	2	Emissions|N2O	kt N2O/yr
1	Emissions	3	Emissions|N2O|AFOLU	kt N2O/yr
1	Emissions	3	Emissions|N2O|Energy	kt N2O/yr
1	Emissions	3	Emissions|N2O|Other	kt N2O/yr
1	Emissions	3	Emissions|NH3	Mt NH3/yr
1	Emissions	3	Emissions|NOx	Mt NOx/yr
1	Emissions	3	Emissions|OC	Mt OC/yr
1	Emissions	3	Emissions|PM10	Mt PM10/yr
1	Emissions	3	Emissions|PM2.5	Mt PM2.5/yr
1	Emissions	3	Emissions|Sulfur	Mt SO2/yr
1	Emissions	3	Emissions|VOC	Mt VOC/yr
1	Energy	1	Capacity Additions|Electricity|Biomass	GW/yr
1	Energy	1	Capacity Additions|Electricity|Biomass|w/ CCS	GW/yr
1	Energy	1	Capacity Additions|Electricity|Biomass|w/o CCS	GW/yr
1	Energy	1	Capacity Additions|Electricity|Coal	GW/yr
1	Energy	1	Capacity Additions|Electricity|Coal|w/ CCS	GW/yr
1	Energy	1	Capacity Additions|Electricity|Coal|w/o CCS	GW/yr
1	Energy	1	Capacity Additions|Electricity|Gas	GW/yr
1	Energy	1	Capacity Additions|Electricity|Gas|w/ CCS	GW/yr
1	Energy	1	Capacity Additions|Electricity|Gas|w/o CCS	GW/yr
1	Energy	1	Capacity Additions|Electricity|Geothermal	GW/yr
1	Energy	1	Capacity Additions|Electricity|Hydro	GW/yr
1	Energy	1	Capacity Additions|Electricity|Nuclear	GW/yr
1	Energy	1	Capacity Additions|Electricity|Oil	GW/yr
1	Energy	1	Capacity Additions|Electricity|Oil|w/ CCS	GW/yr
1	Energy	1	Capacity Additions|Electricity|Oil|w/o CCS	GW/yr
1	Energy	1	Capacity Additions|Electricity|Solar	GW/yr
1	Energy	1	Capacity Additions|Electricity|Solar|CSP	GW/yr
1	Energy	1	Capacity Additions|Electricity|Solar|PV	GW/yr
1	Energy	1	Capacity Additions|Electricity|Storage Capacity	GWh/yr
1	Energy	1	Capacity Additions|Electricity|Transmissions Grid	GWkm/yr
1	Energy	1	Capacity Additions|Electricity|Wind	GW/yr
1	Energy	1	Capacity Additions|Electricity|Wind|Offshore	GW/yr
1	Energy	1	Capacity Additions|Electricity|Wind|Onshore	GW/yr
1	Energy	3	Capacity|Biogas	EJ/yr

1	Energy	3	Capacity|Biogas|w/ CCS	EJ/yr
1	Energy	3	Capacity|Biogas|w/o CCS	EJ/yr
1	Energy	3	Capacity|Biomass Liquids	EJ/yr
1	Energy	3	Capacity|Biomass Liquids|w/ CCS	EJ/yr
1	Energy	3	Capacity|Biomass Liquids|w/o CCS	EJ/yr
1	Energy	1	Capacity|Electricity	GW
1	Energy	1	Capacity|Electricity|Biomass	GW
1	Energy	1	Capacity|Electricity|Biomass|w/ CCS	GW
1	Energy	1	Capacity|Electricity|Biomass|w/o CCS	GW
1	Energy	1	Capacity|Electricity|Coal	GW
1	Energy	1	Capacity|Electricity|Coal|w/ CCS	GW
1	Energy	1	Capacity|Electricity|Coal|w/o CCS	GW
1	Energy	1	Capacity|Electricity|Gas	GW
1	Energy	1	Capacity|Electricity|Gas|CC	GW
1	Energy	1	Capacity|Electricity|Gas|CC|w/ CCS	GW
1	Energy	1	Capacity|Electricity|Gas|CC|w/o CCS	GW
1	Energy	1	Capacity|Electricity|Gas|CT	GW
1	Energy	1	Capacity|Electricity|Gas|CT|w/ CCS	GW
1	Energy	1	Capacity|Electricity|Gas|CT|w/o CCS	GW
1	Energy	1	Capacity|Electricity|Gas|ST	GW
1	Energy	1	Capacity|Electricity|Gas|ST|w/ CCS	GW
1	Energy	1	Capacity|Electricity|Gas|ST|w/o CCS	GW
1	Energy	1	Capacity|Electricity|Gas|w/ CCS	GW
1	Energy	1	Capacity|Electricity|Gas|w/o CCS	GW
1	Energy	1	Capacity|Electricity|Geothermal	GW
1	Energy	1	Capacity|Electricity|Hydro	GW
1	Energy	1	Capacity|Electricity|Net Peak Demand|Day	Day
1	Energy	1	Capacity|Electricity|Net Peak Demand|Hour	Hour
1	Energy	1	Capacity|Electricity|Net Peak Demand|Level	GW
1	Energy	1	Capacity|Electricity|Nuclear	GW
1	Energy	1	Capacity|Electricity|Ocean	GW
1	Energy	1	Capacity|Electricity|Oil	GW
1	Energy	1	Capacity|Electricity|Oil|w/ CCS	GW
1	Energy	1	Capacity|Electricity|Oil|w/o CCS	GW
1	Energy	1	Capacity|Electricity|Other	GW
1	Energy	1	Capacity|Electricity|Solar	GW
1	Energy	1	Capacity|Electricity|Solar|CSP	GW
1	Energy	1	Capacity|Electricity|Solar|PV	GW
1	Energy	1	Capacity|Electricity|Storage Capacity	GW
1	Energy	1	Capacity|Electricity|Storage Capacity|Battery	GW
1	Energy	1	Capacity|Electricity|Storage Capacity|Other	GW

1	Energy	1	Capacity|Electricity|Storage Capacity|PSH	GW
1	Energy	1	Capacity|Electricity|Storage Energy	GWh
1	Energy	1	Capacity|Electricity|Storage Energy|Battery	GWh
1	Energy	1	Capacity|Electricity|Storage Energy|Other	GWh
1	Energy	1	Capacity|Electricity|Storage Energy|PSH	GWh
1	Energy	1	Capacity|Electricity|Transmissions Grid	GWkm
1	Energy	1	Capacity|Electricity|Wind	GW
1	Energy	1	Capacity|Electricity|Wind|Offshore	GW
1	Energy	1	Capacity|Electricity|Wind|Onshore	GW
1	Energy	4	Capacity|Hydrogen|Biomass|w/ CCS	EJ/yr
1	Energy	4	Capacity|Hydrogen|Biomass|w/o CCS	EJ/yr
1	Energy	4	Capacity|Hydrogen|Coal|w/ CCS	EJ/yr
1	Energy	4	Capacity|Hydrogen|Electrolysis	EJ/yr
1	Energy	4	Capacity|Hydrogen|Ethanol	EJ/yr
1	Energy	4	Capacity|Hydrogen|Gas|w/ CCS	EJ/yr
1	Energy	4	Capacity|Hydrogen|Gas|w/o CCS	EJ/yr
1	Energy	4	Capacity|Hydrogen|Photoelectrochemical	EJ/yr
1	Energy	4	Capacity|Hydrogen|Thermochemical	EJ/yr
1	Energy	4	Capacity|Liquids|Oil	EJ/yr
1	Energy	4	Capacity|Synthetic Gas	EJ/yr
1	Energy	4	Capacity|Synthetic Liquids	EJ/yr
1	Energy	1	Final Energy	EJ/yr
1	Energy	1	Final Energy|Biogas	EJ/yr
1	Energy	1	Final Energy|Biomass Liquids	EJ/yr
1	Energy	1	Final Energy|Biomass Solids	EJ/yr
1	Energy	1	Final Energy|Buildings	EJ/yr
1	Energy	1	Final Energy|Buildings|Biogas	EJ/yr
1	Energy	1	Final Energy|Buildings|Biomass Liquids	EJ/yr
1	Energy	1	Final Energy|Buildings|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Buildings|Coal	EJ/yr
1	Energy	2	Final Energy|Buildings|Commercial	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Biogas	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Electricity	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Hydrogen|NG blend	EJ/yr

1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Oil	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Appliances|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Buildings|Commercial|Biogas	EJ/yr
1	Energy	2	Final Energy|Buildings|Commercial|Biomass Liquids	EJ/yr
1	Energy	2	Final Energy|Buildings|Commercial|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Cooling|Electricity	EJ/yr
1	Energy	2	Final Energy|Buildings|Commercial|Electricity	EJ/yr
1	Energy	2	Final Energy|Buildings|Commercial|Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Biogas	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Electricity	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Oil	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Heating|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Buildings|Commercial|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Lighting|Electricity	EJ/yr
1	Energy	2	Final Energy|Buildings|Commercial|Oil	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Biogas	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Electricity	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Oil	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Commercial|Other|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Buildings|Commercial|Synthetic Gas	EJ/yr
1	Energy	2	Final Energy|Buildings|Commercial|Synthetic Liquids	EJ/yr

1	Energy	1	Final Energy|Buildings|Electricity	EJ/yr
1	Energy	1	Final Energy|Buildings|Gas	EJ/yr
1	Energy	1	Final Energy|Buildings|Hydrogen	EJ/yr
1	Energy	2	Final Energy|Buildings|Hydrogen|Direct use	EJ/yr
1	Energy	2	Final Energy|Buildings|Hydrogen|Fuel cell	EJ/yr
1	Energy	2	Final Energy|Buildings|Hydrogen|NG blend	EJ/yr
1	Energy	1	Final Energy|Buildings|Oil	EJ/yr
1	Energy	2	Final Energy|Buildings|Residential	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Biogas	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Electricity	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Oil	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Appliances|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Buildings|Residential|Biogas	EJ/yr
1	Energy	2	Final Energy|Buildings|Residential|Biomass Liquids	EJ/yr
1	Energy	2	Final Energy|Buildings|Residential|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Cooling|Electricity	EJ/yr
1	Energy	2	Final Energy|Buildings|Residential|Electricity	EJ/yr
1	Energy	2	Final Energy|Buildings|Residential|Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Biogas	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Electricity	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Oil	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Heating|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Buildings|Residential|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Hydrogen|Direct use	EJ/yr

1	Energy	3	Final Energy|Buildings|Residential|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Lighting|Electricity	EJ/yr
1	Energy	2	Final Energy|Buildings|Residential|Oil	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Biogas	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Electricity	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Oil	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Buildings|Residential|Other|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Buildings|Residential|Synthetic Gas	EJ/yr
1	Energy	2	Final Energy|Buildings|Residential|Synthetic Liquids	EJ/yr
1	Energy	1	Final Energy|Buildings|Synthetic Gas	EJ/yr
1	Energy	1	Final Energy|Buildings|Synthetic Liquids	EJ/yr
1	Energy	1	Final Energy|Coal	EJ/yr
1	Energy	1	Final Energy|Direct Air Capture	EJ/yr
1	Energy	3	Final Energy|Direct Air Capture|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Direct Air Capture|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Direct Air Capture|Coal	EJ/yr
1	Energy	3	Final Energy|Direct Air Capture|Electricity	EJ/yr
1	Energy	3	Final Energy|Direct Air Capture|Gas	EJ/yr
1	Energy	3	Final Energy|Direct Air Capture|Oil	EJ/yr
1	Energy	1	Final Energy|Electricity	EJ/yr
1	Energy	1	Final Energy|Gas	EJ/yr
1	Energy	1	Final Energy|Geothermal	EJ/yr
1	Energy	1	Final Energy|Heat	EJ/yr
1	Energy	1	Final Energy|Hydrogen	EJ/yr
1	Energy	2	Final Energy|Hydrogen|Direct use	EJ/yr
1	Energy	1	Final Energy|Industry	EJ/yr
1	Energy	1	Final Energy|Industry|Biogas	EJ/yr
1	Energy	1	Final Energy|Industry|Biomass Liquids	EJ/yr
1	Energy	1	Final Energy|Industry|Biomass Solids	EJ/yr
1	Energy	4	Final Energy|Industry|Chemical Feedstocks|Biomass	EJ/yr
1	Energy	4	Final Energy|Industry|Chemical Feedstocks|Gas	EJ/yr
1	Energy	4	Final Energy|Industry|Chemical Feedstocks|Gas|Other	EJ/yr

1	Energy	4	Final Energy|Industry|Chemical Feedstocks|Gas|Petrochemicals	EJ/yr
1	Energy	4	Final Energy|Industry|Chemical Feedstocks|Oil	EJ/yr
1	Energy	4	Final Energy|Industry|Chemical Feedstocks|Oil|Other	EJ/yr
1	Energy	4	Final Energy|Industry|Chemical Feedstocks|Oil|Petrochemicals	EJ/yr
1	Energy	1	Final Energy|Industry|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Aluminum|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|EInt Mfg|Biogas	EJ/yr
1	Energy	2	Final Energy|Industry|EInt Mfg|Biomass Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|EInt Mfg|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Ag chemicals|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Biomass Liquids	EJ/yr

1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Inorganic|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Oil	EJ/yr

1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Organic|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Resins|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Bulk chemicals|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Cement and lime|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|EInt Mfg|Coal	EJ/yr
1	Energy	2	Final Energy|Industry|EInt Mfg|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Biomass Solids	EJ/yr

1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Food products|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|EInt Mfg|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Glass|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|EInt Mfg|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Synthetic Gas	EJ/yr

1	Energy	3	Final Energy|Industry|EInt Mfg|Iron and steel|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|EInt Mfg|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Other|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|EInt Mfg|Paper|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|EInt Mfg|Synthetic Gas	EJ/yr
1	Energy	2	Final Energy|Industry|EInt Mfg|Synthetic Liquids	EJ/yr
1	Energy	1	Final Energy|Industry|Electricity	EJ/yr
1	Energy	1	Final Energy|Industry|Gas	EJ/yr
1	Energy	1	Final Energy|Industry|Hydrogen	EJ/yr
1	Energy	2	Final Energy|Industry|Hydrogen|Direct use	EJ/yr
1	Energy	2	Final Energy|Industry|Hydrogen|Fuel cell	EJ/yr
1	Energy	2	Final Energy|Industry|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Biogas	EJ/yr

1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Crops|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Forestry|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Biomass Solids	EJ/yr

1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Other|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Agriculture|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|Non Mfg|Biogas	EJ/yr
1	Energy	2	Final Energy|Industry|Non Mfg|Biomass Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|Non Mfg|Biomass Solids	EJ/yr
1	Energy	2	Final Energy|Industry|Non Mfg|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Coal mining|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Hydrogen|NG blend	EJ/yr

1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Construction|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|Non Mfg|Electricity	EJ/yr
1	Energy	2	Final Energy|Industry|Non Mfg|Gas	EJ/yr
1	Energy	2	Final Energy|Industry|Non Mfg|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Hydrogen|NG blend	EJ/yr
1	Energy	2	Final Energy|Industry|Non Mfg|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Oil-gas extraction|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other mining|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Biomass Solids	EJ/yr

1	Energy	3	Final Energy|Industry|Non Mfg|Other|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|Non Mfg|Other|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|Non Mfg|Synthetic Gas	EJ/yr
1	Energy	2	Final Energy|Industry|Non Mfg|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Balance of manufacturing|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|NonEInt Mfg|Biogas	EJ/yr
1	Energy	2	Final Energy|Industry|NonEInt Mfg|Biomass Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|NonEInt Mfg|Biomass Solids	EJ/yr
1	Energy	2	Final Energy|Industry|NonEInt Mfg|Coal	EJ/yr
1	Energy	2	Final Energy|Industry|NonEInt Mfg|Electricity	EJ/yr
1	Energy	2	Final Energy|Industry|NonEInt Mfg|Gas	EJ/yr
1	Energy	2	Final Energy|Industry|NonEInt Mfg|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Hydrogen|NG blend	EJ/yr

1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Appliances|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Synthetic Gas	EJ/yr

1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Computer|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Fab metal|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Hydrogen|Fuel cell	EJ/yr

1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Machinery|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Metal durables|Transport equip|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|NonEInt Mfg|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Hydrogen|Fuel cell	EJ/yr

1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Plastic & rubber|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Industry|NonEInt Mfg|Synthetic Gas	EJ/yr
1	Energy	2	Final Energy|Industry|NonEInt Mfg|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Biogas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Biomass Solids	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Coal	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Electricity	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Hydrogen|Direct use	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Hydrogen|Fuel cell	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Hydrogen|NG blend	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Oil	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Industry|NonEInt Mfg|Wood Products|Synthetic Liquids	EJ/yr
1	Energy	1	Final Energy|Industry|Oil	EJ/yr
1	Energy	1	Final Energy|Industry|Synthetic Gas	EJ/yr
1	Energy	1	Final Energy|Industry|Synthetic Liquids	EJ/yr
1	Energy	1	Final Energy|Oil	EJ/yr
1	Energy	3	Final Energy|Oil|Diesel	EJ/yr
1	Energy	3	Final Energy|Oil|Gasoline	EJ/yr
1	Energy	3	Final Energy|Oil|Jet Fuel	EJ/yr
1	Energy	1	Final Energy|Synthetic Gas	EJ/yr
1	Energy	1	Final Energy|Synthetic Liquids	EJ/yr
1	Energy	1	Final Energy|Transportation	EJ/yr
1	Energy	1	Final Energy|Transportation|Biogas	EJ/yr
1	Energy	1	Final Energy|Transportation|Biomass Liquids	EJ/yr
1	Energy	1	Final Energy|Transportation|Electricity	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Aviation|Biogas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Aviation|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Aviation|Electricity	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Aviation|Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Aviation|Hydrogen	EJ/yr

1	Energy	3	Final Energy|Transportation|Freight|Aviation|Oil	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Aviation|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Aviation|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Transportation|Freight|Biogas	EJ/yr
1	Energy	2	Final Energy|Transportation|Freight|Biomass Liquids	EJ/yr
1	Energy	2	Final Energy|Transportation|Freight|Electricity	EJ/yr
1	Energy	2	Final Energy|Transportation|Freight|Gas	EJ/yr
1	Energy	2	Final Energy|Transportation|Freight|Hydrogen	EJ/yr
1	Energy	2	Final Energy|Transportation|Freight|Oil	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Rail|Biogas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Rail|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Rail|Electricity	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Rail|Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Rail|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Rail|Oil	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Rail|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Rail|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Road|Biogas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Road|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Road|Electricity	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Road|Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Road|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Road|Oil	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Road|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Road|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Shipping|Biogas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Shipping|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Shipping|Electricity	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Shipping|Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Shipping|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Shipping|Oil	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Shipping|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Freight|Shipping|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Transportation|Freight|Synthetic Gas	EJ/yr
1	Energy	2	Final Energy|Transportation|Freight|Synthetic Liquids	EJ/yr
1	Energy	1	Final Energy|Transportation|Gas	EJ/yr
1	Energy	1	Final Energy|Transportation|Hydrogen	EJ/yr
1	Energy	2	Final Energy|Transportation|Offroad|Biogas	EJ/yr
1	Energy	2	Final Energy|Transportation|Offroad|Biomass Liquids	EJ/yr
1	Energy	2	Final Energy|Transportation|Offroad|Electricity	EJ/yr
1	Energy	2	Final Energy|Transportation|Offroad|Gas	EJ/yr

1	Energy	2	Final Energy|Transportation|Offroad|Hydrogen	EJ/yr
1	Energy	2	Final Energy|Transportation|Offroad|Oil	EJ/yr
1	Energy	2	Final Energy|Transportation|Offroad|Synthetic Gas	EJ/yr
1	Energy	2	Final Energy|Transportation|Offroad|Synthetic Liquids	EJ/yr
1	Energy	1	Final Energy|Transportation|Oil	EJ/yr
1	Energy	2	Final Energy|Transportation|Oil|Diesel	EJ/yr
1	Energy	2	Final Energy|Transportation|Oil|Gasoline	EJ/yr
1	Energy	2	Final Energy|Transportation|Oil|Jet Fuel	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Aviation|Biogas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Aviation|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Aviation|Electricity	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Aviation|Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Aviation|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Aviation|Oil	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Aviation|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Aviation|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Transportation|Passenger|Biogas	EJ/yr
1	Energy	2	Final Energy|Transportation|Passenger|Biomass Liquids	EJ/yr
1	Energy	2	Final Energy|Transportation|Passenger|Electricity	EJ/yr
1	Energy	2	Final Energy|Transportation|Passenger|Gas	EJ/yr
1	Energy	2	Final Energy|Transportation|Passenger|Hydrogen	EJ/yr
1	Energy	2	Final Energy|Transportation|Passenger|Oil	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Other|Biogas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Other|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Other|Electricity	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Other|Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Other|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Other|Oil	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Other|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Other|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Rail|Biogas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Rail|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Rail|Electricity	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Rail|Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Rail|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Rail|Oil	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Rail|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Rail|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Road|Biogas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Road|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Road|Electricity	EJ/yr

1	Energy	3	Final Energy|Transportation|Passenger|Road|Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Road|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Road|Oil	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Road|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Road|Synthetic Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Shipping|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Shipping|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Passenger|Shipping|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Transportation|Passenger|Synthetic Gas	EJ/yr
1	Energy	2	Final Energy|Transportation|Passenger|Synthetic Liquids	EJ/yr
1	Energy	2	Final Energy|Transportation|Pipeline	EJ/yr
1	Energy	3	Final Energy|Transportation|Pipeline|Biogas	EJ/yr
1	Energy	3	Final Energy|Transportation|Pipeline|Biomass Liquids	EJ/yr
1	Energy	3	Final Energy|Transportation|Pipeline|Electricity	EJ/yr
1	Energy	3	Final Energy|Transportation|Pipeline|Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Pipeline|Hydrogen	EJ/yr
1	Energy	3	Final Energy|Transportation|Pipeline|Oil	EJ/yr
1	Energy	3	Final Energy|Transportation|Pipeline|Synthetic Gas	EJ/yr
1	Energy	3	Final Energy|Transportation|Pipeline|Synthetic Liquids	EJ/yr
1	Energy	1	Final Energy|Transportation|Synthetic Gas	EJ/yr
1	Energy	1	Final Energy|Transportation|Synthetic Liquids	EJ/yr
1	Energy	1	Primary Energy	EJ/yr
1	Energy	1	Primary Energy|Biomass	EJ/yr
1	Energy	1	Primary Energy|Biomass|Modern	EJ/yr
1	Energy	1	Primary Energy|Biomass|Modern|w/ CCS	EJ/yr
1	Energy	1	Primary Energy|Biomass|Modern|w/o CCS	EJ/yr
1	Energy	2	Primary Energy|Biomass|Traditional	EJ/yr
1	Energy	1	Primary Energy|Coal	EJ/yr
1	Energy	1	Primary Energy|Coal|w/ CCS	EJ/yr
1	Energy	1	Primary Energy|Coal|w/o CCS	EJ/yr
1	Energy	1	Primary Energy|Fossil	EJ/yr
1	Energy	1	Primary Energy|Fossil|w/ CCS	EJ/yr
1	Energy	1	Primary Energy|Fossil|w/o CCS	EJ/yr
1	Energy	1	Primary Energy|Gas	EJ/yr
1	Energy	1	Primary Energy|Gas|w/ CCS	EJ/yr
1	Energy	1	Primary Energy|Gas|w/o CCS	EJ/yr
1	Energy	1	Primary Energy|Geothermal	EJ/yr
1	Energy	1	Primary Energy|Hydro	EJ/yr
1	Energy	2	Primary Energy|Non-Biomass Renewables	EJ/yr
1	Energy	1	Primary Energy|Nuclear	EJ/yr
1	Energy	1	Primary Energy|Ocean	EJ/yr

1	Energy	1	Primary Energy|Oil	EJ/yr
1	Energy	1	Primary Energy|Oil|w/ CCS	EJ/yr
1	Energy	1	Primary Energy|Oil|w/o CCS	EJ/yr
1	Energy	1	Primary Energy|Other	EJ/yr
1	Energy	1	Primary Energy|Solar	EJ/yr
1	Energy	1	Primary Energy|Wind	EJ/yr
1	Energy	1	Production|Primary Energy|Coal	EJ/yr
1	Energy	1	Production|Primary Energy|Gas	EJ/yr
1	Energy	1	Production|Primary Energy|Oil	EJ/yr
1	Energy	1	Secondary Energy|Biogas	EJ/yr
1	Energy	2	Secondary Energy|Biogas|Biomass|Input	EJ/yr
1	Energy	3	Secondary Energy|Biogas|Energy Crops	EJ/yr
1	Energy	1	Secondary Energy|Biogas|Input	EJ/yr
1	Energy	3	Secondary Energy|Biogas|Other	EJ/yr
1	Energy	2	Secondary Energy|Biogas|Other|Input	EJ/yr
1	Energy	3	Secondary Energy|Biogas|Residues	EJ/yr
1	Energy	3	Secondary Energy|Biogas|w/ CCS	EJ/yr
1	Energy	3	Secondary Energy|Biogas|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Biomass Liquids	EJ/yr
1	Energy	2	Secondary Energy|Biomass Liquids|Biomass|Input	EJ/yr
1	Energy	3	Secondary Energy|Biomass Liquids|Energy Crops	EJ/yr
1	Energy	1	Secondary Energy|Biomass Liquids|Input	EJ/yr
1	Energy	3	Secondary Energy|Biomass Liquids|Other	EJ/yr
1	Energy	2	Secondary Energy|Biomass Liquids|Other|Input	EJ/yr
1	Energy	3	Secondary Energy|Biomass Liquids|Residues	EJ/yr
1	Energy	3	Secondary Energy|Biomass Liquids|w/ CCS	EJ/yr
1	Energy	3	Secondary Energy|Biomass Liquids|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Biomass	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Biomass|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Biomass|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Coal	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Coal|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Coal|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Curtailment	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Gas	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Gas|CC	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Gas|CC|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Gas|CC|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Gas|CT	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Gas|CT|w/ CCS	EJ/yr

1	Energy	1	Secondary Energy|Electricity|Gas|CT|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Gas|ST	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Gas|ST|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Gas|ST|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Gas|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Gas|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Geothermal	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Hydro	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Hydrogen	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Biogas	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Biogas|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Biogas|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Biomass Solids	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Biomass Solids|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Biomass Solids|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Coal	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Coal|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Coal|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Gas	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Gas|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Gas|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Hydrogen	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Oil	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Oil|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Oil|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Synthetic Gas	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Input|Synthetic Liquids	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Losses	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Losses|Storage	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Losses|T&D	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Net exports	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Non-Biomass Renewables	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Nuclear	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Ocean	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Oil	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Oil|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Oil|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Solar	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Solar|CSP	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Solar|PV	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Storage	EJ/yr

1	Energy	1	Secondary Energy|Electricity|Storage|Battery	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Storage|Other	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Storage|PSH	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Synthetic Gas	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Synthetic Liquids	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Wind	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Wind|Offshore	EJ/yr
1	Energy	1	Secondary Energy|Electricity|Wind|Onshore	EJ/yr
1	Energy	2	Secondary Energy|Heat	EJ/yr
1	Energy	3	Secondary Energy|Heat|Biomass	EJ/yr
1	Energy	3	Secondary Energy|Heat|Coal	EJ/yr
1	Energy	3	Secondary Energy|Heat|Gas	EJ/yr
1	Energy	3	Secondary Energy|Heat|Geothermal	EJ/yr
1	Energy	3	Secondary Energy|Heat|Nuclear	EJ/yr
1	Energy	3	Secondary Energy|Heat|Oil	EJ/yr
1	Energy	3	Secondary Energy|Heat|Other	EJ/yr
1	Energy	3	Secondary Energy|Heat|Solar	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Biomass	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Biomass|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Biomass|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Coal	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Coal|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Coal|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Electrolysis	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Ethanol	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Gas	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Gas|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Gas|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Input	EJ/yr
1	Energy	2	Secondary Energy|Hydrogen|Input|Biomass Liquids	EJ/yr
1	Energy	4	Secondary Energy|Hydrogen|Input|Biomass Liquids|w/ CCS	EJ/yr
1	Energy	4	Secondary Energy|Hydrogen|Input|Biomass Liquids|w/o CCS	EJ/yr
1	Energy	2	Secondary Energy|Hydrogen|Input|Biomass Solids	EJ/yr
1	Energy	4	Secondary Energy|Hydrogen|Input|Biomass Solids|w/ CCS	EJ/yr
1	Energy	4	Secondary Energy|Hydrogen|Input|Biomass Solids|w/o CCS	EJ/yr
1	Energy	2	Secondary Energy|Hydrogen|Input|Coal	EJ/yr
1	Energy	4	Secondary Energy|Hydrogen|Input|Coal|w/ CCS	EJ/yr
1	Energy	4	Secondary Energy|Hydrogen|Input|Coal|w/o CCS	EJ/yr
1	Energy	2	Secondary Energy|Hydrogen|Input|Electricity	EJ/yr
1	Energy	2	Secondary Energy|Hydrogen|Input|Gas	EJ/yr

1	Energy	4	Secondary Energy|Hydrogen|Input|Gas|w/ CCS	EJ/yr
1	Energy	4	Secondary Energy|Hydrogen|Input|Gas|w/o CCS	EJ/yr
1	Energy	2	Secondary Energy|Hydrogen|Input|Nuclear	EJ/yr
1	Energy	2	Secondary Energy|Hydrogen|Input|Oil	EJ/yr
1	Energy	4	Secondary Energy|Hydrogen|Input|Oil|w/ CCS	EJ/yr
1	Energy	4	Secondary Energy|Hydrogen|Input|Oil|w/o CCS	EJ/yr
1	Energy	2	Secondary Energy|Hydrogen|Input|Other	EJ/yr
1	Energy	2	Secondary Energy|Hydrogen|Input|Solar	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Oil	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Oil|w/ CCS	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Oil|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Other	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Photoelectrochemical	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Thermochemical	EJ/yr
1	Energy	1	Secondary Energy|Hydrogen|Thermochemical|Nuclear	EJ/yr
1	Energy	1	Secondary Energy|Petroleum Refining	EJ/yr
1	Energy	2	Secondary Energy|Petroleum Refining|Input	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Biogas	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Biomass Liquids	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Biomass Solids	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Coal	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Electricity	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Gas	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Hydrogen	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Hydrogen|Direct Use	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Hydrogen|Fuel Cell	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Hydrogen|NG Blend	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Oil	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Synthetic Gas	EJ/yr
1	Energy	3	Secondary Energy|Petroleum Refining|Input|Synthetic Liquids	EJ/yr
1	Energy	2	Secondary Energy|Petroleum Refining|w/ CCS	EJ/yr
1	Energy	2	Secondary Energy|Petroleum Refining|w/o CCS	EJ/yr
1	Energy	1	Secondary Energy|Synthetic Gas	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Gas|Coal|w/ CCS	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Gas|Electricity	EJ/yr
1	Energy	2	Secondary Energy|Synthetic Gas|Electricity|Input	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Gas|Gas|w/ CCS	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Gas|Hydrogen	EJ/yr
1	Energy	2	Secondary Energy|Synthetic Gas|Hydrogen|Input	EJ/yr
1	Energy	1	Secondary Energy|Synthetic Gas|Input	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Gas|Nuclear	EJ/yr

1	Energy	3	Secondary Energy|Synthetic Gas|Oil|w/ CCS	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Gas|Other	EJ/yr
1	Energy	2	Secondary Energy|Synthetic Gas|Other|Input	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Gas|Solar	EJ/yr
1	Energy	1	Secondary Energy|Synthetic Liquids	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Liquids|Coal|w/ CCS	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Liquids|Electricity	EJ/yr
1	Energy	2	Secondary Energy|Synthetic Liquids|Electricity|Input	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Liquids|Gas|w/ CCS	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Liquids|Hydrogen	EJ/yr
1	Energy	2	Secondary Energy|Synthetic Liquids|Hydrogen|Input	EJ/yr
1	Energy	1	Secondary Energy|Synthetic Liquids|Input	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Liquids|Nuclear	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Liquids|Oil|w/ CCS	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Liquids|Other	EJ/yr
1	Energy	2	Secondary Energy|Synthetic Liquids|Other|Input	EJ/yr
1	Energy	3	Secondary Energy|Synthetic Liquids|Solar	EJ/yr
1	Energy	3	Trade|Primary Energy|Biomass|Volume	EJ/yr
1	Energy	3	Trade|Primary Energy|Coal|Volume	EJ/yr
1	Energy	3	Trade|Primary Energy|Gas|Volume	EJ/yr
1	Energy	3	Trade|Primary Energy|Oil|Volume	EJ/yr
1	Energy Service	2	Energy Service|Floor Space|Buildings|Index	Index 2020=1
1	Energy Service	3	Energy Service|Floor Space|Buildings|Value	million m2
1	Energy Service	2	Energy Service|Floor Space|Commercial|Index	Index 2020=1
1	Energy Service	3	Energy Service|Floor Space|Commercial|Value	million m2
1	Energy Service	2	Energy Service|Floor Space|Residential|Index	Index 2020=1
1	Energy Service	3	Energy Service|Floor Space|Residential|Value	million m2
1	Energy Service	2	Energy Service|Transportation|Freight|Aviation|Index	Index 2020=1
1	Energy Service	3	Energy Service|Transportation|Freight|Aviation|Value	million tkm/yr
1	Energy Service	4	Energy Service|Transportation|Freight|BEV|Sales Share	%
1	Energy Service	4	Energy Service|Transportation|Freight|BEV|Stock Share	%
1	Energy Service	4	Energy Service|Transportation|Freight|FCEV|Sales Share	%
1	Energy Service	4	Energy Service|Transportation|Freight|FCEV|Stock Share	%
1	Energy Service	4	Energy Service|Transportation|Freight|HEV|Sales Share	%

1	Energy Service	4	Energy Service|Transportation|Freight|HEV|Stock Share	%
1	Energy Service	4	Energy Service|Transportation|Freight|ICE|Sales Share	%
1	Energy Service	4	Energy Service|Transportation|Freight|ICE|Stock Share	%
1	Energy Service	2	Energy Service|Transportation|Freight|Index	Index 2020=1
1	Energy Service	2	Energy Service|Transportation|Freight|Other|Index	Index 2020=1
1	Energy Service	3	Energy Service|Transportation|Freight|Other|Value	million tkm/yr
1	Energy Service	4	Energy Service|Transportation|Freight|PHEV|Sales Share	%
1	Energy Service	4	Energy Service|Transportation|Freight|PHEV|Stock Share	%
1	Energy Service	2	Energy Service|Transportation|Freight|Rail|Index	Index 2020=1
1	Energy Service	3	Energy Service|Transportation|Freight|Rail|Value	million tkm/yr
1	Energy Service	2	Energy Service|Transportation|Freight|Road|Index	Index 2020=1
1	Energy Service	3	Energy Service|Transportation|Freight|Road|Value	million tkm/yr
1	Energy Service	3	Energy Service|Transportation|Freight|Value	million tkm/yr
1	Energy Service	2	Energy Service|Transportation|Passenger|Aviation|Index	Index 2020=1
1	Energy Service	3	Energy Service|Transportation|Passenger|Aviation|Value	million pkm/yr
1	Energy Service	4	Energy Service|Transportation|Passenger|BEV|Sales Share	%
1	Energy Service	4	Energy Service|Transportation|Passenger|BEV|Stock Share	%
1	Energy Service	2	Energy Service|Transportation|Passenger|Bicycling and Walking|Index	Index 2020=1
1	Energy Service	3	Energy Service|Transportation|Passenger|Bicycling and Walking|Value	million pkm/yr
1	Energy Service	4	Energy Service|Transportation|Passenger|FCEV|Sales Share	%
1	Energy Service	4	Energy Service|Transportation|Passenger|FCEV|Stock Share	%
1	Energy Service	4	Energy Service|Transportation|Passenger|HEV|Sales Share	%
1	Energy Service	4	Energy Service|Transportation|Passenger|HEV|Stock Share	%
1	Energy Service	4	Energy Service|Transportation|Passenger|ICE|Sales Share	%
1	Energy Service	4	Energy Service|Transportation|Passenger|ICE|Stock Share	%
1	Energy Service	2	Energy Service|Transportation|Passenger|Index	Index 2020=1
1	Energy Service	2	Energy Service|Transportation|Passenger|Other|Index	Index 2020=1

1	Energy Service	3	Energy Service|Transportation|Passenger|Other|Value	million pkm/yr
1	Energy Service	4	Energy Service|Transportation|Passenger|PHEV|Sales Share	%
1	Energy Service	4	Energy Service|Transportation|Passenger|PHEV|Stock Share	%
1	Energy Service	2	Energy Service|Transportation|Passenger|Rail|Index	Index 2020=1
1	Energy Service	3	Energy Service|Transportation|Passenger|Rail|Value	million pkm/yr
1	Energy Service	2	Energy Service|Transportation|Passenger|Road|Index	Index 2020=1
1	Energy Service	3	Energy Service|Transportation|Passenger|Road|Value	million pkm/yr
1	Energy Service	3	Energy Service|Transportation|Passenger|Value	million pkm/yr
1	Land	3	Agricultural Production	Million t DM/yr
1	Land	2	Agricultural Production|Energy	Million t DM/yr
1	Land	3	Agricultural Production|Energy|Crops	Million t DM/yr
1	Land	3	Agricultural Production|Energy|Residues	Million t DM/yr
1	Land	2	Agricultural Production|Non-Energy	Million t DM/yr
1	Land	3	Agricultural Production|Non-Energy|Crops	Million t DM/yr
1	Land	3	Agricultural Production|Non-Energy|Livestock	Million t DM/yr
1	Policy	2	Policy Cost|Equivalent Variation|Quintile 1	billion US$2018/yr
1	Policy	2	Policy Cost|Equivalent Variation|Quintile 2	billion US$2018/yr
1	Policy	2	Policy Cost|Equivalent Variation|Quintile 3	billion US$2018/yr
1	Policy	2	Policy Cost|Equivalent Variation|Quintile 4	billion US$2018/yr
1	Policy	2	Policy Cost|Equivalent Variation|Quintile 5	billion US$2018/yr
1	Policy	1	Price|Carbon	US$2018/t CO2
1	Trade	4	Trade|Secondary Energy|Biogas|Value	billion US$2018/yr
1	Trade	3	Trade|Secondary Energy|Biogas|Volume	EJ/yr
1	Trade	4	Trade|Secondary Energy|Biomass Liquids|Value	billion US$2018/yr
1	Trade	3	Trade|Secondary Energy|Biomass Liquids|Volume	EJ/yr
1	Trade	4	Trade|Secondary Energy|Biomass Solids|Value	billion US$2018/yr
1	Trade	3	Trade|Secondary Energy|Biomass Solids|Volume	EJ/yr
1	Trade	4	Trade|Secondary Energy|Electricity|Value	billion US$2018/yr

1	Trade	3	Trade|Secondary Energy|Electricity|Volume	EJ/yr
1	Trade	4	Trade|Secondary Energy|Hydrogen|Value	billion US$2018/yr
1	Trade	3	Trade|Secondary Energy|Hydrogen|Volume	EJ/yr
1	Trade	4	Trade|Secondary Energy|Oil|Value	billion US$2018/yr
1	Trade	3	Trade|Secondary Energy|Oil|Volume	EJ/yr
1	Trade	4	Trade|Secondary Energy|Synthetic Gas|Value	billion US$2018/yr
1	Trade	3	Trade|Secondary Energy|Synthetic Gas|Volume	EJ/yr
1	Trade	4	Trade|Secondary Energy|Synthetic Liquids|Value	billion US$2018/yr
1	Trade	3	Trade|Secondary Energy|Synthetic Liquids|Volume	EJ/yr

Bibliography

Adachi Y, Hosono S, Iio J (eds) (2015) Policy analysis in Japan APERC (2019) APEC Energy Demand and Supply Outlook 7th Edition, volume I.

Agency for Natural Resources and Energy (2018) Current status of renewable energy in Japan and overseas, and proposal points for this year's procurement price calculation committee, document 1 (in Japanese).

Agency for Natural Resources and Energy (2020) Website for information disclosure on the Feed-in Tarrif (in Japanese). Agency NatResour Energy. https ://www.fit-porta l.go.jp/Publi cInfo Summary.Accessed 7 Sep 2020

Agency for Natural Resources and Energy Japan (2019) Energy white paper 2019 Bloomberg New Energy Finance (2019) New energy outlook 2019.

Aguiar, A., Chepeliev, M., Corong, E. L., McDougall, R., and van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis*, 4(1):1–27.

Aguiar, A., Narayanan, B., and McDougall, R. (2016). An Overview of the GTAP 9 Data Base. *Journal of Global Economic Analysis*, 1(1):181–208.

Aguiar, A., Chepeliev, M., Corong, E. L., McDougall, R., and van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis*, 4(1):1–27.

Åhman M, Nilsson LJ, Johansson B (2017) Global climate policy and deep decarbonization of energy-intensive industries energy intensive industries, 3062. Doi: https ://doi.org/10.1080/14693 062.2016.11670 09

Akashi O, Hijioka Y, Masui T, Hanaoka T, Kainuma M (2012) GHG emission scenarios in Asia and the world: the key technologies for significant reduction. Energy Econ 34(SUPPL. 3):S346–S358.https ://doi.org/10.1016/j.eneco .2012.04.011

Ang BW (2000) A survey of index decomposition analysis in energy and environmental studies. Energy 25:1149–1176.

Armington, P. S. (1969). A Theory of Demand for Products Distinguished by Place of Production. *Staff Papers-International Monetary Fund*, pages 159–178.

Asayama S, Ishii A (2014) Media representations and governance of CCS: framings and policy implications of Japanese newspaper's coverage. Soc Tech Res Essay Collect 11:127–137. https ://doi.org/10.3392/socio techn ica.11.127

Ashina S, Fujino J, Masui T, Ehara T, Hibino G (2012) A roadmap towards a low-carbon society in Japan using back casting methodology: Feasible pathways for achieving an 80% reduction in CO2 emissions by 2050. Energy Policy 41:584–598. https ://doi. org/10.1016/j.enpol .2011.11.020

Atkinson, A. B. (1970). On the measurement of inequality. *Journal of economic theory*, 2(3):244–263.

Axelson M, Robson I, Khandekar G, Wyns T (2018) Breaking through: Industrial Low-CO2 Technologies on the Horizon. 92. www.ies.be/Breaking-Through_Repor t_13072 018

Balistreri, E. J., Böhringer, C., and Rutherford, T. F. (2018). Carbon policy and the structure of global trade. The World Economy, 41(1):194–221.

Bataille C, Åhman M, Neuhoff K, Nilsson LJ, Fischedick M, Lechtenböhmer S et al (2018) A review of technology and policy deep decarbonization pathway options for making energy intensive industry production consistent with the Paris Agreement. J Clean Prod 187:960–973. https ://doi.org/10.1016/j.jclepro.2018.03.107

Birat, J (2011) The sustainability footprint of steelmaking. Steel Times Int 35:42 Davis SJ, Lewis NS, Shaner M, Aggarwal S, Arent D, Azevedo IL et al (2018). Net-zero emissions energy systems. Science. https://doi.org/10.1126/scien ce.aas97 93

Bistline, JE, Hodson E, Rossmann, CG, et al (2018). Electric sector policy, technological change, and U.S. emissions reductions goals: Results from the EMF 32 model intercomparison project. Energy Econ 73:307–325. https://doi.org/10.1016/j.eneco.2018.04.012

Bovenberg, A. L. and R. de Mooij (1994). "Environmental Levies and Distortionary Taxation," American Economic Review, Vol. 84, No. 4, pp 1085-1089.

Bovenberg, A. L. and L.H. Goulder (1996). "Optimal Environmental Taxes Taxation in the Presence of Other Taxes: General Equilibrium Analysis," American Economic Review, Vol. 86, No. 4, pp. 985-1000.

Bovenberg, A. L. and L.H Goulder (1997). “Costs of Environmentally Motivated Taxes in the Presence of Other Taxes: General Equilibrium Analysis,” *National Tax Journal*, Vol. 50, No. 1.

Bruce, J.P., H. Lee, and E.F. Haites (1996). Climate Change 1995- Volume 3: *Economic and Social Dimensions of Climate Change*, Cambridge University Press. Cambridge, United Kingdom.

Calculation Committee for Procurement Price E (2019) Opinion on procurement price etc. for FY2019 and beyond.

Calvin K, Clarke L, Krey V, et al (2012) The role of Asia in mitigating climate change: Results from the Asia modeling exercise. Energy Econ 34:S251S260.https: //doi.org/10.1016/j.eneco.

Cherp A, Vinichenko V, Jewell J et al (2017) Comparing electricity transitions: a historical analysis of nuclear, wind and solar power in Germany and Japan. Energy Policy 101:612–628. https ://doi.org/10.1016/j.enpol .2016.10.044

Clarke LE, Fawcett AA, Weyant JP et al (2014) Technology and U.S. emissions reductions goals: results of the EMF 24 modeling exercise. Energy J 35:9–31. https ://doi.org/10.5547/01956 574.35.SI1.2.

COMMIT (2019) Deliverable 2.2: Long-term, Low-emission Pathways in Australia, Brazil, Canada, China, EU, India, Indonesia, Japan, Republic of Korea, Russia, and United States

Dai H, Fujimori S, Silva Herran D et al (2017) The impacts on climate mitigation costs of considering curtailment and storage of variable renewable energy in a general equilibrium model. Energy Econ 64:627–637. https ://doi.org/10.1016/j.eneco .2016.03.002.

Dowlatabadi, H. and M. Oravetz (1997). “U.S. Long-Term Energy Intensity: Backcast and Projection,” working paper, Dept. of Engineering and Public Policy, Carnegie Mellon University.

ECRA (European Cement Research Academy, 2017). CSI/ECRA technology papers 2017: development of state-of-the-art techniques in cement manufacturing: trying to look ahead. http:// docs.wbcsd .org/2017/06/CSI_ECRA Technology Papers_2017.pdf

EECRstee. (2011) Proceedings of the first international conference on energy efficiency and CO2 reduction in the steel industry, HIsarna Pilot Plant Project, Meijer, K., Guenther, C., Dry, R.J., 27 June to 1 July 2011, Dusseldorf, 2011.

Edmonds, J., M.J. Scott, J.M. Roop, and C. MacCracken. (1999). "International Emissions Trading & Global Climate Change: Impacts on the Costs of Greenhouse Gas Mitigation," Pew Center of Global Climate Change, Washington, D.C.

Ehrlich PR, Holdren JP (1971). Impact of population growth. ObstetGynecol Surv 26(11):769. https ://doi.org/10.1097/00006 254-19711 1000-00014

EIA (2017). *International Energy Outlook 2017*. U.S. Energy Information Administration.

EIA (2019). International Energy Statistics. https://www.eia.gov/beta/international/data/browser/.

Energy Modeling Forum (EMF, 1977). *Report I: Energy and the Economy.* Stanford University. California. Energy Modeling Forum (EMF, 1978) *Report* 2: *Coal in Transition: I 980--2000.* Stanford University, California.

Energy Modeling Forum (EMF, 1979) *Report* 3: *Electric Load Forecasting: Probing the Issues with Models*, Stanford University, California.

Energy Modeling Forum (EMF, 1980/81). *Report* 4: *Aggregate Elasticity of Energy Demand.* Stanford University, California. (Vol. I reprinted (1981) *Energy JI* 2(2~37-76.)

Energy Modeling Forum (EMF, 1982). *Report* 5: *US Oil and Gas Supply*. Energy Modeling Forum, Stanford University, Stanford, California.

Energy Modeling Forum (EMF 6, 1981) *Report* 6: *World Oil.* Energy Modeling Forum, Stanford University, California.

Energy Modeling Forum (EMF 7, 1984). *Report* 7: *Macroeconomic Impacts of Energy Shocks.* Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 8, 1987). *Report* 8: *Industrial Energy Demand.* Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 9, 1989). *Report* 9: *North American Natural Gas Markets*,. Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 10, 1990). *Report 10: Electricity Markets and Planning*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 11, 1991). *Report 11: International Oil Supplies and Demands*, “Volumes 1 and 2 (1992), Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 12, 1993). *Report 12:* Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 13, 1996). *Report 13: Markets for Energy Efficiency*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 14, 1996). *Report 14: Integrated Assessment of Climate Change*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 15, 1998). *Report 15: A Competitive Electricity Industry*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 16, 1999). *Report 16: The Costs of the Kyoto Protocol*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 17, 2002). *Report 17: Prices and Emissions in a Restructured Electricity Market*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 18, 2002). *Report 18: International Trade Dimensions Of Climate Policies*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 19, 2004). *Report 19: Climate Change: Technology Strategies and International Trade*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 20, 2004). *Report 20: Natural Gas, Fuel Diversity and North American Energy Markets*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 21, 2006). *Report 21: Multi-Gas Mitigation and Climate Change*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 22, 2009). *Report 22: Climate Change Transition Scenarios*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 23, 2009). *Report 23: World Natural Gas Markets and Trade*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 24, 2014). *Report 24: The EMFF24 Study on U.S. Technology and Climate Policy Strategy*, published as a special Issue of the Energy Journal, Fawcett, A. L. Clarke and J. Weyant (editors), Volume 35, Special Issue No. 1, 255 pp. ISSN 0195-6574e-iS SN 1944-9089.

Energy Modeling Forum (EMF 25, 2011). *Report 25: Energy Efficiency and Climate Change*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 26, 2013. *Report 26: Changing the Game? Emissions and Market Implications of New Natural Gas Supplies*, Stanford University, Stanford, CA.

Energy Modeling Forum (EMF 27, 2014). *Report 27: The EMF27 Study on Global Technology and Climate Policy Strategies*, published as a double special issue of Climatic Change, Weyant, J, E. Kreigler, G. Blanford, V. Krey, J. Edmonds, Keywan Riahi, Richard Richels, Massimo Tavoni (editors), Volume 123, Issue 3-4, April 2014. ISSN: 0165-0009 (Print) 1573-1480 (Online)

Energy Modeling Forum (EMF 28, 2013). *Report 28: Introduction To The EMF 28 Study on Scenarios for Transforming The European Energy System*, published as a special issue of Climate Change Economics, Volume 4, ISSN (print): 2010-0078 | ISSN (online): 2010-0086

Energy Modeling Forum (EMF 29, 2012). *Report 29: The Role of Border Carbon Adjustment in Unilateral Climate Policy: Results from EMF 29* published as a special issue of Energy Economics, Böhringer, C., E. Balistreri, T. Rutherford (editors), Volume 34, Supplement 2, Pages S95-S250 (December 2012).

Energy Modeling Forum (EMF 30, 2020). *Report 30: Short-Lived Climate Forcers (SLCF) and Air Quality*" special issue of Climatic Change, John Weyant, Steven J Smith, and Zbigniew Klimont (editors), 163:1399–1408, https://doi.org/10.1007/s10584-020-02938-5.

Energy Modeling Forum (EMF 31, 2015). Report 31: *North American Natural Gas Markets in Transition*, Stanford University, Stanford. CA.

Energy Modeling Forum (EMF 32-1,2018). *Report 32a: U.S. Carbon Tax Scenarios*, special issue of Climate Change Economics, Fawcett, A.A, J. McFarland, A. C. Morris and J. P. Weyant (editors), Vol. 9, No. 1 (2018) 1840001

Energy Modeling Forum (EMF 32-2, 2018), Report 32b: *The EMF 32 Study On Technology And Climate Policy Strategies For Greenhouse Gas Reductions In The U.S. Electric Power Sector*, special Issue of Energy Economics, Bistline, J., J. Creason, B. Murray (editors), Volume 73.

Energy Modeling Forum (EMF 33, 2020), Report 33. *Assessing Large-scale Global Bioenergy Deployment for Managing Climate Change (EMF-33)***,** Special issue of Climatic Change, S. Rose, J. Weyant, N. Bauer, S. Fuminori, P. Havlik, A. Popp, D. van Vuuren, and M. Wise (editors), Volume 163, issue 3.

Energy Modeling Forum (EMF 34, 2021). Report 34: *North American Energy Integration: Lessons from EMF 34.* Special Issue of Energy Policy, Edited by John Weyant, Hillard Huntington, Abha Bhargava, David Daniels.

Energy Modeling Forum (EMF 35, 2021). Report 35: *Energy Scenarios for Long-Term Climate Change Mitigation in Japan*, Special Issue of Sustainability Science, Sugiyama, M., Fujimori, S., Wada, K. Weyant, J. (editors), https://doi.org/10.1007/s11625-021-00913-2, ISSN: 1862-4065 (Print) 1862-4057 (Online).

Energy Modeling Forum 36 (EMF, 2021). Report 36: *Post-Paris Carbon Pricing,* Special Issue of Energy Economics, Sonja Peterman, Christopher Boeringer and Thomas Rutherford (Editors).

Energy Modeling Forum 37 (EMF, 2021). *Preliminary EMF 37 Study Design,* McFarland, J., A Fawcett, T. Mai, G. Blanford, and J. Weyant, Energy Modeling Forum, Stanford University, Stanford, CA.

European Commission (2013) Technology map of the european strategic energy technology plan (SET-Plan). https ://ec.europ a.eu/jrc/ en/print pdf/15540 2

Energy Information Administration. 1998a. "Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity," SR/OIAF/98-03, Washington, D.C.

Energy Information Administration. 1998b. "The National Energy Modeling System: An Overview (1998)," DOE/EIA-0581(98), Washington, D.C.

Fawcett AA, Clarke LC, Rausch S, Weyant JP (2014a) Overview of EMF 24 Policy Scenarios. Energy J 35:. https://doi.org/10.5547/01956574.35.SI1.3

Fawcett AA, Clarke LE, Weyant JP (2014b) Introduction to EMF 24. Energy J 35:. https://doi.org/10.5547/01956574.35.SI1.1

Fawcett AA, McFarland JR, Morris AC, Weyant JP (2018) INTRODUCTION TO THE EMF 32 STUDY ON U.S. CARBON TAX SCENARIOS. Clim Change Econ 09:1840001. https://doi.org/10.1142/S2010007818400018

Federation of Electric Power Companies of Japan (2018) Japanese version of connect & manage for expanded introduction of renewable energies.

Fischedick M, Marzinkowski J, Winzer P, Weigel M (2014) Technoeconomic evaluation of innovative steel production technologies. J Clean Prod 84:563–580. https ://doi.org/10.1016/j.jclep ro.2014.05.063

Fujimori S, Kainuma M, Masui T, Hasegawa T, Dai H (2014) The effectiveness of energy service demand reduction: a scenario analysis of global climate change mitigation. Energy Policy 75:379–391. https ://doi.org/10.1016/j.enpol .2014.09.01

Fujimori, S., Kubota, I., Dai, H., Takahashi, K., Hasegawa, T., Liu, J.-Y., Hijioka, Y., Masui, T., and Takimi, M. (2016). Will international emissions trading help achieve the objectives of the Paris agreement? *Environmental Research Letters*, 11(10):104001.

Fujimori S, Hasegawa T, Masui T, et al (2017) SSP3: AIM implementation of Shared Socioeconomic Pathways. Glob Environ Change 42:268–283. https://doi.org/10.1016/j.gloenvcha.2016.06.009

Fujimori S, Oshiro K, Shiraki H, Hasegawa T (2019) Energy transformation cost for the Japanese mid-century strategy. Nat Commun10:1–11. https ://doi.org/10.1038/s4146 7-019-12730 -4

Fullerton, D. and Muehlegger, E. (2019). Who Bears the Economic Burdens of Environmental Regulations? *Review of Environmental Economics and Policy*, 13(1):62–82.

Gartner E, Sui T (2017) Alternative cement clinkers. Cem Concr Res. https ://doi.org/10.1016/j.cemco nres.2017.02.002

GoJ (Government of Japan, 2015). Submission of Japan’s intended nationally determined contribution (INDC). http://www4. unfcc c.int/submissions/INDC/ Published%20Documents/ Japan/1/20150717_Japan’s%20INDC.pdf.

GoJ (2016) The plan for global warming countermeasure. http://www.env.go.jp/press /files /jp/10281 6.pdf [in Japanese]

G o u l d e r, L.H. (1995). “Environmental Taxation and the Double Dividend: A Reader’s Guide,” International Tax and Public Finance, Vol. 2, pp. 157-183.

G o u l d e r, L. H. and K. Mathai (2000). "Optimal CO2 Abatement in the Presence Of Induced Technological Change," Journal of Environmental Economics and Management, Vol. 39, pp. 1-38.

G o u l d e r, L. H. and S. H. Schneider (1999). "Induced Technological Change and the Attractiveness of CO2 A b a t e m e n t Policies," *Resource and Energy Economics*, Vol. 2, pp 211-253.

Government of Japan (2020). Green Growth Strategy Accompanying the 2050 Carbon Neutrality (2050 nen kahbon nyuhtoraritih ni tomonau grihn seicho senryaku)
Government of Japan (2015) Submission of Japan's Intended Nationally Determined Contribution (INDC)

Government of Japan (2019). The Long-term Strategy under the Paris Agreement

Grubler A, Wilson C, Bento N, Boza-kiss B, Krey V, Mccollum DL et al (2018). A low energy demand scenario for meeting the 15 °C target and sustainable development goals without negative emission technologies. Nat Energy. https ://doi.org/10.1038/s4156
0-018-0172-6

Hayhoe, K., A. Jain, H. Pitcher, C. MacCracken, M. Gibbs, D. Wuebbles, R. Harvey, and D. Kruger (1999). "Costs of Multigreenhouse Gas Reduction Targets for the U.S.A," *Science*, Vol. 286, pp. 905-906. 29 October.

Hertwich, EG, Coauthors (2019). Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. Environ Res Lett. https ://doi.org/10.1088/1748-9326/ab0fe 3

Hills TP, Sceats M, Rennie D, Fennell P (2017). LEILAC: Low cost CO2 capture for the cement and lime industries. Energy procedia, vol 114. Elsevier, Amsterdam, pp 6166–6170

Hills T, Leeson D, Florin N, Fennell P (2016). Carbon capture in the cement industry: technologies, progress, and retrofitting. EnvironSci Technol 50:368–377. https ://doi.org/10.1021/acs.est.5b035 08

Hodson EL, Brown M, Cohen S, et al (2018). U.S. energy sector impacts of technology innovation, fuel price, and electric sector CO2 policy: Results from the EMF 32 model intercomparison study. Energy Econ 73:352–370. https://doi.org/10.1016/j.eneco.2018.03.027

Hof, A. F., den Elzen, M. G., Admiraal, A., Roelfsema, M., Gernaat, D. E., andvan Vuuren, D. P. (2017). Global and regional abatement costs of nationally determined contributions (NDCs) and of enhanced action to levels well below 2 c and 1.5 c. Environmental Science & Policy, 71:30–40.

ICAP (International Carbon Action Partnership, 2020a). Japan—saitama target setting emissions trading system. https://icapcarbonaction. com/en/?option=com_etsmap&task=export&format= pdf&layout=list&systems[]=84

ICAP (2020b). Japan—Tokyo cap-and-trade program. https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format= pdf&layout=list&systems[]=51

ICEF (Innovation for Cool Earth Forum) (2016). ICEF innovation roadmap 1.0: CO2 utilization and ZEB/ZEH roadmaps released at COP22. https ://www.icef-forum .org/platform/artic le_detail.php?artic le__id=109

IEA (International Energy Agency) (2016). World energy balances 2016. OECD Publishing, Paris. https ://doi.org/10.1787/9789264263 116-en

IEA (2017a). Energy technology perspectives 2017—executive summary. International Energy Agency (IEA) Publications, 371. Doi:https ://doi.org/10.1787/energy_tech-2014-en

IEA (2017). Renewable Energy for Industry: From green energy to green materials and fuels. OECD Publishing, Paris. https ://doi. org/10.3138/97814 87595 753-006

IEA (2018). *World Energy Outlook 2018*. International Energy Agency.
Kitous, A., Keramidas, K., Vandyck, T., and Saveyn, B. (2016). GECO 2016: Global Energy and Climate Outlook: Road from Paris: Impact of climate policies on global energy markets in the context of the UNFCCC Paris Agreement. Text.

IEA (2019). Tracking industry, IEA, Paris https ://www.iea.org/reports/tracking-industry
IPCC (Intergovernmental Panel on Climate Change) (2014) Fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press 2014. https ://www.ipcc.ch/site/asset s/uploads/2018/02/ipcc_wg3_ar5_full.pdf

International Energy Agency (2011). Harnessing variable renewables: a guide to the balancing challenge. Organisation for Economic Co-operation and Development, Paris
International Energy Agency (2019) Japan solar PV auctions. https://www.iea.org/policies/6563-japan -solar -pv-auctions?country=Japan &region=Asia Pacific. Accessed 7 May 2020

International Renewable Energy Agency (2019). Renewable power generation costs in 2018

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES (2016). The methodological assessment report on scenarios and models of biodiversity and ecosystem services.

IPCC (2018). Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pörtner H-O, et al. (eds) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland, p 32

IPCC (2018). Proposed outline of the special report in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate cha. IPCC - Sr15, 2(October), 17–20. www.environmentalgraphiti.org

IPCC (2018). Summary for policymakers. In: Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D JS, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor TW (eds) Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. World Meteorological Organization, Geneva

Itaoka K, Saito A, Sasaki K (2017). Public perception on hydrogen infrastructure in Japan: influence of rollout of commercial fuel cell vehicles. Int J Hydrogen Energy 42:7290–7296. https ://doi.org/10.1016/j.ijhyd ene.2016.10.123

IPSS (2017) Population Projections for Japan (2017): 2016 to 2065. National Institute of Population and Social Security Research JBF (Japan Business Federation) (2019). KEIDANREN’s commitment to a low carbon society fiscal 2018 follow-up results. https ://www.keida nren.or.jp/policy/vape.html

Jacoby , H.D. and I. Sue Wing (1999). “Adjustment Time, Capital Malleability and Policy Cost,” in Weyant op. cit.

JBF (2014). Low carbon society action plan independent evaluation committee evaluation report. https ://www.keida nren.or.jp/policy/2015/039.pdf

Japan CCS (2020). Information disclosure system for Tomakomai CCS verification test. http://www.jccs-tomak omai monit oring.com/JCCS/wp-content/uploads/2020/03/20200 3.pdf. Accessed 7 May 2020

Japan Nuclear Safety Institute (2020). Nuclear power plant operation record [original in Japanese]. http://www.genan shin.jp/db/fm/plant statusN.php?x=d. Accessed 7 May 2020

JCA (Japan Cement Association) (2013). Cement industry's efforts to combat global warming. http://www.jcass oc.or.jp/seisankankyo/seisa n02/pdf/seisa n02_01.pdf

JCA (2014). Low carbon society action plan phase II (cement industry).http://www.jcass oc.or.jp/cement/4pdf/jg1k_03.pdf

JISF (Japan Iron and Steel Federation, 2014) Low carbon society action plan phase II (iron and steel industry). https ://www.jisf. or.jp/business/ondan ka/kouke n/keika ku/documents/14111 2.pdf

JISF (2019). Long-term vision for climate change mitigation A challenge towards zero-carbon steel, 2019. http://www.jisf.or.jp/business/ondan ka/zerocarbon steel /

Ju Y, Sugiyama M, Silva Herran D, et al (2021a). Industrial Decarbonization Under Japan's National Mitigation Scenarios: A Multi-Model Analysis. Sustain Sci

Ju Y, Sugiyama M, Silva Herran D, et al (2021b). An open-source tool for visualization of climate mitigation scenarios: mipplot. Environ Model Softw Rev (in revision)

Jorgenson, D.W. and P.J. Wilcoxen (1993). "Energy, The Environment and Economic Growth," in: *Handbook of Natural Resources and Energy Economics*, A. Kneese and J. Sweeney, Editors, North Holland, 1993, pp.1267-1349.

Jorgenson, D. W. and P.J. Wilcoxen (1995). "Reducing U.S. Carbon Emissions: An Econometric General Equilibrium Assessment," in D. Gaskins and J. Weyant, Editors, Reducing Global Carbon Emissions: Costs and Policy Options, Energy Modeling Forum, Stanford University, Stanford, CA.

Kainuma M, Masui T, Oshiro K, Hibino G (2015). Pathways to deep decarbonization in Japan. SDSN - IDDRI

Kann, A. and J. P. Weyant (2000). “Approaches For Performing Uncertainty Analysis In Large-Scale Energy /Economic Policy Models,” *Environmental Modeling and Assessment*, Vol. 5. No.1, pp. 29-46.

Kato E, Kurosawa A (2019). Evaluation of Japanese energy system toward 2050 with TIMES-Japan: deep decarbonization pathways. Energy procedia. Elsevier Ltd, London, pp 4141–4146

Kawase R, Matsuoka Y (2015). Steel production estimation in Japan with considering global market, Proceedings of the Civil Engineering Society (Environment), vol 71, No. 5, I_383–394. https ://www.jstag e.jst.go.jp/artic le/jscej er/71/5/71_I_383/_pdf

Kaya Y (1990). Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios. In: paper presented to the IPCC energy and industry subgroup, response strategies working group.

Kimura K (2018). Analysis of wind power costs in Japan Kimura K, Zissler R (2016) Comparing prices and costs of solar PV in Japan and Germany, Tokyo

Klein, L. R. and J.Y Park (1995). “The University of Pennsylvania Model for High-Frequency Economic Forecasting, ” *Economic and Financial Modeling*, Vol. 2, No. 3, pp. 95-146.

Kline, S. and N. Rosenberg (1986). “An Overview of Innovation,” in: *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, R. Landau and N. Rosenberg, Editors, National Academy Press, Washington, D.C.

Knopf B, Henry Chen Y, DE Cian E et al (2013). Beyond 2020-strategies and costs for transforming the European energy system. Clim Chang Econ. https ://doi.org/10.1142/S2010 00781 34000 10

Komiyama R, Fujii Y (2014). Assessment of massive integration of photovoltaic system considering rechargeable battery in Japan with high time-resolution optimal power generation mix model. Energy Policy 66:73–89. https ://doi.org/10.1016/j.enpol.2013.11.022

Komiyama R, Fujii Y (2015). Long-term scenario analysis of nuclear energy and variable renewables in Japan’s power generation mix considering flexible power resources. Energy Policy 83:169–184.https ://doi.org/10.1016/j.enpol .2015.04.005

Komiyama R, Fujii Y (2017). Assessment of post-Fukushima renewable energy policy in Japan’s nation-wide power grid. Energy Policy 101:594–611. https ://doi.org/10.1016/j.enpol .2016.11.006

Komiyama R, Fujii Y (2021). No decarbonization of power generation mix and the role of offshore wind power integration in Japan. Sustain Science.

Knopf B, Chen Y-HH, De Cian E, et al (2013). BEYOND 2020 — STRATEGIES AND COSTS FOR TRANSFORMING THE EUROPEAN ENERGY SYSTEM. Clim Change Econ 04:1340001. https://doi.org/10.1142/S2010007813400010

Kriegler E, Riahi K, Bauer N, et al (2015). Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. Technol Forecast Soc Change 90:24–44. https://doi.org/10.1016/j.techfore.2013.09.021

Koopmans, T.C., R.E. Litan, and J.P. Weyant (1977). Energy Modeling for an Uncertain Future, Committee on Nuclear and Alternative Energy Systems, Modeling Resource Group of the Synthesis Panel, National Research Council, December.

Kriegler E, Weyant JP, Blanford GJ, et al (2014). The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. Clim Change 123:353–367. https://doi.org/10.1007/s10584-013-0953-7

Kuramochi T, Ramírez A, Turkenburg W, Faaij A (2012). Comparative assessment of CO2 capture technologies for carbon-intensive industrial processes. Prog Energy Combust Sci 38(1):87–112.https ://doi.org/10.1016/j.pecs.2011.05.001

Kuramochi T (2016). Assessment of midterm CO2 emissions reduction potential in the iron and steel industry : a case of Japan. J Clean Prod 132:81–97. https ://doi.org/10.1016/j.jclepro.2015.02.055

Kuriyama A, Tamura K, Kuramochi T (2019). Can Japan enhance its 2030 greenhouse gas emission reduction targets? Assessment of economic and energy-related assumptions in Japan's NDC. Energy Policy 130(April):328–340. https ://doi.org/10.1016/j.enpol .2019.03.055

LANDES (2011). Product details of CO2-SUICOM. https ://www.landes.co.jp/product/113

Leeson D, Fennell P, Shah N, Petit C, Mac Dowell N (2017). A Technoeconomic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries. Int J Greenh Gas Control 61:71–84. https ://doi.org/10.1016/j.ijggc .2017.03.020

Lehne J, Preston F (2018). Making concrete change innovation in low carbon cement and concrete. Chatham House Rep. https ://doi.org/10.1088/1742-6596/1015/3/03216 3

Lemos MC, Arnott JC, Ardoin NM, et al (2018). To co-produce or not to co-produce. Nat Sustain 1:722–724. https://doi.org/10.1038/s41893-018-0191-0

Lovins, A.B. (1976). *Energy Strategy: The Road Not Taken?* Foreign Affairs, October.

Lucena AFP, Clarke L, Schaeffer R, et al (2016). Climate policy scenarios in Brazil: A multimodel comparison for energy. Energy Econ 56:564–574. https://doi.org/10.1016/j.eneco.2015.02.005

Lugovoy O, Feng X-Z, Gao J, et al (2018). Multi-model comparison of CO 2 emissions peaking in China: Lessons from CEMF01 study. Adv Clim Change Res 9:1–15. https://doi.org/10.1016/j.accre.2018.02.001

Luderer G, Krey V, Calvin K et al (2014). The role of renewable energy in climate stabilization: results from the EMF27 scenarios. Clim Change 123:427–441. https ://doi.org/10.1007/s1058 4-013-0924-z

Luderer G, Pietzcker RC, Carrara S et al (2017). Assessment of wind and solar power in global low-carbon energy scenarios: an introduction. Energy Econ 64:542–551. https ://doi.org/10.1016/j.eneco.2017.03.027

Manne, A.S., and R. G. Richels (1999). "The Kyoto Protocol: A Cost-Effective Strategy for Meeting Environmental Objectives?" in Weyant op. cit.

Manne, A.S., and R. G. Richels (2000). "A Multi-gas Approaches to Climate Policy," Working Paper, Stanford University, Stanford, CA.

Mccollum DL, Gambhir A, Rogelj J, Wilson C (2020). Energy modellers should explore extremes more. Nat Energy. https ://doi.org/10.1038/s4156 0-020-0555-3

McMillan C, Boardman R, McKellar M, Sabharwall P, Ruth M, Bragg-Sitton S (2016). Generation and use of thermal energy in the US industrial sector and opportunities to reduce its carbon emissions.

METI (Ministry of Economy, Trade, and Industry) (2013). Japan's policy on energy conservation. https ://eneke n.ieej.or.jp/data/4746.pdf

METI (2015a). Top runner program: developing the world's best energy efficient appliance and more. 2015. https ://www.enech o.meti.go.jp/category/saving_and_new/saving/data/toprunner2 015e.pdf

METI (2015b). Chouki enerugi jyukyu mitoshi (long-term energy outlook, in Japanese). The subcommittee on long-term energy supply and demand outlook. https ://www.enech o.meti.go.jp/committee/council/basic policysubcommittee/mitos hi/pdf/report_01.pdf

METI (2016). Long-term global warming counter measure platform (Choki Chikyu Ondanka Taisaku Prattohommu). http://www.meti. go.jp/press /2017/04/20170 41400 6/20170 41400 6-1.pdf.

METI (2017). Connected industries Tokyo initiative 2017, https ://www.meti.go.jp/polic y/monoinfoservice/connectedindus tries /index.html

METI (2018). Fifth energy basic plan. https ://www.enech o.meti.go.jp/category/others/basic plan/#head

METI (2019a). 2018 annual report on energy (energy white paper), https ://www.enech o.meti.go.jp/about /white paper/

METI (2019b). Large-scale CCS Demonstration Project in Hokkaido Prefecture, Successfully Injects 300,000 Tons of CO2 cumulatively, https ://www.meti.go.jp/english/press /2019/1125_004.html

METI (2019c). Innovative Environmental Innovation Strategy. https://www.meti.go.jp/shing ikai/energyenvironment/kankyoinnovation /003.html

METI (2020). 2019 Manufacturing white paper (annual report based on article 8 of the basic act on the promotion of basic manufacturing technology). https ://www.meti.go.jp/repor t/white paper/mono/2019/index .html

MOE (Ministry of the Environment 2007). Keynote speech by ichirokamoshita, minister of the environment of Japan. 2007. https ://www.env.go.jp/earth /g8/en/meeting/img/Keyno te%20Spe ech%20by%20Ich iro%20Kam oshit a%20in%20the %20Ses sion%20on%20 Climate%20Change.pdf

MOE (2008). Action plan for creating a low-carbon society. http://www.env.go.jp/press /fileview.php?seria l=11912 &houid=10025

MOE (2014). Tax to combat global warming. https ://www.env.go.jp/policy/tax/faq.html

MOE (2016a). Long-term, low-carbon vision. http:// www.env.go.jp/press /10382 2/10547 8.pdf

MOE (2016b). global warming countermeasures plan (Japanese Cabinet Decision). https ://www.env.go.jp/press /10251 2.html

MOE (2019a). Long-term growth strategy based on the Paris Agreement, https ://www.env.go.jp/press /10686 9.html

MOE (2019b). 2018 annual report on environment (environment white paper), http://www.env.go.jp/polic y/hakusyo/

Moore J (2017). Thermal hydrogen: an emissions free hydrocarbon economy. Int J Hydrogen Energy 42:12047–12063. https ://doi.org/10.1016/j.ijhyd ene.2017.03.182

Nameki M, Moriguchi Y (2014). Recent developments in efforts to reduce GHG emissions in the iron and steel sector and their potential reductions in major producer countries. In: Proceedings of the annual conference of the Japan Institute of Energy, vol 23(0), pp 254–255. Doi: https ://doi.org/10.20550 /jieta ikaiy oushi .23.0_254

Masui T, Matsumoto K, Hijioka Y, et al (2011). An emission pathway for stabilization at 6 Wm−2 radiative forcing. Clim Change 109:59‑76. https://doi.org/10.1007/s10584-011-0150-5

Matsuoka K, Kainuma M, Fujino J, Ehara T (2013). How to Approach Asian Low-Carbon Societies? Glob Environ Res 17:3–10

Matsukawa H, Ohigashi T, Yamatani H, Ogimoto K (2017). Study on photovoltaic system installed capacity in Japan [original in Japanese]. In: Proceedings of the annual meeting of the Japan Society of Energy and Resources, pp 161–164

Matsuo Y, Komiyama R (2021). System LCOE of variable renewable energies: a case study of Japan’s long-term GHG mitigation target towards 2050. Sustain Sci

Matsuo Y, Endo S, Nagatomi Y et al (2018). A quantitative analysis of Japan’s optimal power generation mix in 2050 and the role of CO2-free hydrogen. Energy 165:1200–1219. https ://doi.org/10.1016/j.energ y.2018.09.187

Matsuo Y, Endo S, Nagatomi Y et al (2020). Investigating the economics of the power sector under high penetration of variable renewable energies. Appl Energy 267:113956. https ://doi.org/10.1016/j.apene rgy.2019.11395 6

McFarland JR, Fawcett AA, Morris AC, et al (2018). Overview of the emf 32 study on U.S. carbon tax scenarios. Clim Change Econ 09:1840002. https://doi.org/10.1142/S201000781840002X

Morita T, Nakićenović N, Robinson J (2000). Overview of mitigation scenarios for global climate stabilization based on new IPCC emission scenarios (SRES). Environ Econ Policy Stud 3:65–88. https://doi.org/10.1007/BF03354031

Ministerial Council on Renewable Energy Hydrogen and Related Issues (2017).

Basic hydrogen strategy Ministry of Economy Trade and Industry Japan (2017). Implementation of a practical application test of the "energy-saving carbon dioxide separation and capture system" using solid absorbent [original in Japanese]. In: Minist. Econ. Trade Ind. Japan. https :// www.meti.go.jp/press /2017/09/20170 91900 5/20170 91900 5.html.Accessed 20 May 2020

Ministry of Economy Trade and Industry Japan (2019). Cabinet orders concerning the Act of Promoting Utilization of Sea Areas in the Development of Power Generation Facilities Using Maritime Renewable Energy Resources approved. https ://www.meti.go.jp/english/press /2019/0315_003.html. Accessed 7 May 2020

Ministry of Land Infrastructure Transport and Tourism Japan (2019). Efforts to promote offshore wind power generation (report) [original in Japanese]

Ministry of the Environment Japan (2017). Renewable energy introduction potential map and basic zoning information [original in Japanese]. https ://www.env.go.jp/earth /ondan ka/rep/. Accessed 11 May 2020

Ministry of the Environment Japan (2018). First manual of zoning methodology related to wind power generators for local governments [original in Japanese]

Mizuno E (2014). Overview of wind energy policy and development in Japan. Renew Sustain Energy Rev 40:999–1018. https ://doi.org/10.1016/j.rser.2014.07.184

Murray BC, Bistline J, Creason J et al (2018). The EMF 32 study on technology and climate policy strategies for greenhouse gas reductions in the U.S. electric power sector: an overview. Energy Econ 73:286–289

NEDO (New Energy and Industrial Technology Development Organization, 2018). Open innovation white paper. https ://www.nedo.go.jp/library/openinnovationhakus yo.html

NEDO (2019). Annual report of the development of environmentally friendly process technology in Japan. https ://www.nedo.go.jp/conte nt/10090 5230.pdf

New Energy and Industrial Technology Development Organization, Toshiba Energy Systems & Solutions Corporation, Tohoku Electric Power Co. Inc., Iwatani Corporation (2020). The world's largest-class hydrogen production, Fukushima Hydrogen Energy Research Field (FH2R) now is completed at Namie town in Fukushima. https ://www.nedo.go.jp/engli sh/news/AA5en 10042 2.html. Accessed 7 May 2020

Newell, R., A. Jaffe, and R. Stavins (1996). "Environmental Policy And Technological Change: The Effect Of Economic Incentives And Direct Regulation On Energy-Saving Innovation", Working Paper, Harvard University, John F. Kennedy School of Government.

Nikkei (2020). ArcelorMittal: steelmaking without coal, 5 trillion yen investment on natural gas and hydrogen. 2020.09.30. https ://www.nikke i.com/artic le/DGKKZ O6437 1720Z 20C20 A9TJ2 000/

Nordhaus, W.D. (1993). "Optimal Greenhouse Gas Reductions and Tax Policy in the "Dice" Model," *American Economic Review,* May.

Nordhaus, W. D. (1994). *Managing the Global Commons: The Economics of Climate Change*, MIT Press. Cambridge, MA.

Nordhaus, W. D. (1997). "Modeling Induced Innovation in Climate-Change Policy," paper presented at the IIASA/NBER Workshop on Induced Technological Change and the Environment, International Institute for Applied Systems Analysis, Laxenburg, Austria, June 26-27.

Nordhaus, W.D. and J.G. Boyer (1999). "Requiem for Kyoto: An Economic Analysis of the Kyoto Protocol," in Weyant op. cit.

Oda J, Akimoto K, Sano F, Tomoda T (2007). Diffusion of energy efficient technologies and CO2 emission reductions in iron and steel sector. Energy Econ 29:868–888. https ://doi.org/10.1016/j.eneco .2007.01.003

Oda J, Akimoto K (2019). Analysis of energy intensity of basic materials industry in Japan. In: local energy, global markets, 42nd IAEE international conference, May 29-June 1, 2019. International Association for Energy Economics.

Osaki CoolGen Corporation, New Energy and Industrial Technology Development Organization (2019). Starting demonstration tests for oxygen-blown integrated coal gasification combined cycle technology with CO2 capture

Oshiro K, Gi K, Fujimori S, et al (2019). Mid-century emission pathways in Japan associated with the global 2 °C goal: national and global models' assessments based on carbon budgets. Clim Change. https://doi.org/10.1007/s10584-019-02490-x

Oshiro K, Masui T, Kainuma M (2018). Transformation of Japan's energy system to attain net-zero emission by 2050. Carbon Manag 9:493–501. https://doi.org/10.1080/17583004.2017.1396842

Paltsev S, Capros P (2013). Cost concepts for climate change mitigation. Clim Chang Econ. https ://doi.org/10.1142/S2010 00781 34000 34

Parry, I. W. H. (1995). "Pollution Taxes and Revenue Recycling," Journal of Environmental Economics and Management, Vol. 29, No. 3, pp. 564-577.

Peck, S.C. and T. J. Teisberg (1999). "CO2 Emissions Control Agreements: Incentives for Regional Participation, " Working Paper, EPRI.

Pearce, D.W. (1996). The MIT Dictionary of Modern Economics, 4th Edition. MIT Press, Cambridge, MA.

Peters GP, Andrew RM, Canadell JG, Fuss S, Jackson RB, Korsbakken JI et al (2017). Key indicators to track current progress and future ambition of the Paris Agreement. Nat Clim Change. https ://doi.org/10.1038/NCLIM ATE32 02

Power Generation Cost Verification Working Group of Advisory Committee for Natural Resources and Energy Nuclear power (2020). (In Japanese)

Portney, P.R. and J.P. Weyant (1999). Discounting and Intergenerational Equity, Resources for the Future, Washington , D . C .

Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov, and C. Wang (1999). “Multi-gas Assessment of the Kyoto Protocol,” Nature, Vol. 401, pp. 549-555. 7 October.

Riahi, K. (2017). Low-emission pathways in 11 major economies: comparison of cost-optimal pathways and Paris climate proposals. Climatic Change, 142(3-4):491–504.

Rogelj J, Fricko O, Meinshausen M, et al (2017). Understanding the origin of Paris Agreement emission uncertainties. Nat Commun 8:15748. https://doi.org/10.1038/ncomms15748

Shackleton, R., M. Shelby, A. Cristofaro, R. Brinner, J. Yanchar, L. Goulder, D. Jorgenson, P. Wilcoxen, P. Pauly, and R. Kaufman (1996). “The Efficiency Value of Carbon Tax Revenues,” in D. Gaskins and J. Weyant, Editors, Reducing Global Carbon Emissions: Costs and Policy Options, Energy Modeling Forum, Stanford University, Stanford, CA.

Saito T, Urabe C, Ogimoto K (2017). Study on wind turbine installed capacity in Japan (2) [original in Japanese]. In: Proceedings of the annual meeting of the Japan Society of Energy and Resources. pp 165–168

Saito O, Hashimoto S, Managi S, et al (2019). Future scenarios for socio-ecological production landscape and seascape. Sustain Sci 14:1–4. https://doi.org/10.1007/s11625-018-0651-5

Saito A, Itaoka K, Akai M (2019). Those who care about CCS—results from a Japanese survey on public understanding of CCS. Int J Greenh Gas Control 84:121–130. https ://doi.org/10.1016/j.ijggc.2019.02.014

Sakamoto S, Nagai Y, Sugiyama M, et al (2021). End-use decarbonization and electrification: EMF 35 JMIP study. Sustain Sci (in revision)

Schreyer F, Luderer G, Rodrigues R, et al (2020). Common but differentiated leadership: strategies and challenges for carbon neutrality by 2050 across industrialized economies. Environ Res Lett 15:114016. https://doi.org/10.1088/1748-9326/abb852

Scrivener KL, John VM, Gartner EM (2018). Eco-efficient cements: potential economically viable solutions for a low-CO2 cement-based materials industry. Cem Concr Res. https ://doi. org/10.1145/23702 16.2370232

Shiraki H, Ashina S, Kameyama Y et al (2016). Analysis of optimal locations for power stations and their impact on industrial symbiosis planning under transition toward low-carbon power sector in Japan. J Clean Prod 114:81–94. https ://doi.org/10.1016/j.jclep ro.2015.09.079

Shiraki H, Ju Y (2021). EMF 35 JMIP study for Japan's long-term climate and energy policy: scenario designs and key findings. Sustain Sci

Shiraki H, Sugiyama M, Matsuo Y, et al (2021) The role of renewables in the Japanese power sector: implications from the EMF35. Sustain Sci

Shoven, J. B. and Whalley, J. (1992). Applying General Equilibrium. Cambridge university press.

Spencer T, Coauthors (2015). Beyond the Numbers: Understanding the Transformation Induced by INDCs

Silva Herran D, Dai H, Fujimori S, Masui T (2016). Global assessment of onshore wind power resources considering the distance to urban areas. Energy Policy 91:75–86. https ://doi.org/10.1016/j.enpol .2015.12.024

Silva Herran D, Fujimori S, Kainuma M (2019) Implications of Japan's long-term climate mitigation target and the relevance of uncertain nuclear policy. Clim Policy 19:1117–1131. https ://doi.org/10.1080/14693 062.2019.16345 07

Suga Y (2020). Inaugural speech of the prime minister at the 203rd session of the Diet (Dai nihyaku san kai niokeru suga naikaku sohri daijin shoshin hyomei enzetsu)

Sugiyama M, Akashi O, Wada K, Kanudia A, Li J, Weyant J (2014). Energy efficiency potentials for global climate change mitigation. Clim Change 123(3e4):397. https ://doi.org/10.1007/s10584-013-0874-5

Sugiyama M, Fujimori S, Wada K, et al (2019). Japan's long-term climate mitigation policy: Multi-model assessment and sectoral challenges. Energy 167:1120–1131. https://doi.org/10.1016/j.energy.2018.10.091

Sugiyama M, Fujimori S, Wada K, et al (2021). The EMF 35 JMIP study for Japan's long-term climate and energy policy: scenario design and key findings. Sustain Sci

Sugiyama M, Fujimori S, Wada K, et al (2021). EMF 35 JMIP study for Japan's long-term climate and energy policy: scenario designs and key findings UN Environment (ed) (2019) Global Environment Outlook – GEO-6: Healthy Planet, Healthy People:, 1st edn. Cambridge University Press

Sugiyama, M., O. Akashi, K. Wada, A. Kanudia, J. Li, and J. Weyant (2014). Energy efficiency potentials in global climate change mitigation; a comparison of modeling approaches, in Special Issue of Climatic Change Volume 123, pp. 397-411.

The Japan Atomic Energy Relations Organization (2019). The results of a public opinion survey on nuclear energy (In Japanese)

Toshiba Energy Systems & Solutions Corporation (2019). Construction work progresses at large-scale carbon capture demonstration facility. In: Toshiba Energy Syst. Solut. Corporation. https ://www.toshi ba-energ y.com/en/therm al/topic s/ccs-1.htm. Accessed 20 May 2020

United Nations Environment Programme (2020). The emissions gap report 2020

UNFCCC (1994). UN General Assembly, United Nations Framework Convention on Climate Change: Resolution / adopted by the General Assembly, A/RES/48/189. URL: https://unfccc.int/process-and-meetings/theconvention/ what-is-the-united-nations-framework-convention-on-climate-change.

UNFCCC (2020). NDC registry. https://www4.unfccc.int/sites/NDCStaging/pages/All.aspx.
van Soest, H. L., Aleluia Reis, L., Drouet, L., van Vuuren, D. P., den Elzen, M. G. J.,

UNIDO (United Nations Industrial Development Organization (2016). Industrial development report 2016: the role of technology and innovation in inclusive and sustainable industrial development.

UNIDO (2018). Industrial development report 2018. Demand for manufacturing: driving inclusive and sustainable industrial development. https ://www.unido.org/resources-publicatio ns-flags hippublications-industrial -development-report-series/industrial-development-report-2018

Vandyck, T., Keramidas, K., Saveyn, B., Kitous, A., and Vrontisi, Z. (2016). A global stock take of the Paris pledges: Implications for energy systems and economy. Global Environmental Change, 41:46–63.

Van Sluisveld M, De Boer HS, Hof A, Van Vuuren D, Schneider C, Lechtenboehmer S (2019) Comparing quantitative industry decarbonization perspectives towards 2050 for Europe. IAMC 12th Annual Meeting, Tsukuba, Japan. https ://www.iamco nsort ium.org/wp-conte nt/uploa ds/2020/03/van_Sluis veld_NEW.pdf

van Soest, H. L. v., Reis, L. A., Drouet, L., Vuuren, D. P. v., den Elzen, M. G. J., Tavoni, M., Akimoto, K., Calvin, K. V., Fragkos, P., Kitous, A., Luderer, G., Riahi, K. (2017). Low-emission pathways in 11 major economies: comparison of cost-optimal pathways and Paris climate proposals. - Climatic Change, 142, 3, 491-504. https://doi.org/10.1007/s10584-017-1964-6

Vrontisi, Z., Luderer, G., Saveyn, B., Keramidas, K., Lara, A. R., Baumstark, L., Bertram, C., de Boer, H. S., Drouet, L., Fragkiadakis, K., Fricko, O., Fujimori, S., Guivarch, C., Kitous, A., Krey, V., Kriegler, E., Broin, E. Ó., Paroussos, L., andvan Vuuren, D. (2018). Enhancing global climate policy ambition towards a 1.5 c stabilization: A short-term multi-model assessment. Environmental Research Letters, 13(4):044039.

Vogl V, Åhman M, Nilsson LJ (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. J Clean Prod 203:736–745.https ://doi.org/10.1016/j.jclep ro.2018.08.279

Waisman H, Bataille C, Winkler H, et al (2019). A pathway design framework for national low greenhouse gas emission development strategies. Nat Clim Change 9:261–268. https://doi.org/10.1038/s41558-019-0442-8

Wakabayashi M, Arimura TH (2016). Voluntary agreements to encourage proactive firm action against climate change: an empirical study of industry associations' voluntary action plans in Japan. J Clean Prod 112:2885–2895. https ://doi.org/10.1016/j.jclepro.2015.10.071

Watson, R.T, M.Z. Zinyowera, and R.H. Moss (1996). Climate Change 1995-Volume 2: Impacts Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. Cambridge University Press. Cambridge, United Kingdom.

Weyant, J.P.(1978). "A Comparative Analysis of Three of ERDA's Major R & D Programs," Energy - The International Journal, December 1978, Vol. 3, No. 6, pp. 747-768.

Weyant, J.P. editor, (1999). "The Costs of the Kyoto Protocol: A Multi-Model Evaluation," Special Issue of The Energy Journal.

Weyant, J.P., O. Davidson, H. Dowlatabadi, J. Edmonds, M. Grubb, E.A. Parson, R. Richels, J. Rotmans, PR. Shukla, and R.S.J. Tol (1996). "Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results," Chapter 10 in Climate Change 1995: Economic and Social Dimensions of Climate Change, Cambridge University Press, Cambridge.

Weyant, J. P. and Hill, J. (1999). The costs of the Kyoto protocol: A multi-model evaluation: Introduction and overview. The Energy Journal, 20:vii–xliv.

Weyant, J.P., and T. Olavson (1999). "Issues in Modeling Induced Technological Change in Energy, Environmental, and Climate Policy," Environmental Modeling and Assessment, Vol. 4, pp. 67-85.

Weyant, John P. (2001). "Economic Models: How They Work and Why Their Results Differ," in Climate Change: Science, Strategies and Solutions, Eileen Claussen, Executive Editor, The Pew Center on Global Climate Change, Brill, Boston.

Wharton Econometric Forecasting Associates (WETA, 1998). "Global Warming: The High Cost of the Kyoto Protocol, National and State Impacts," Eddystone, PA .

World Bank (2019). World Bank Indicators. https://data.worldbank.org/indicator/.

World Steel Association (2019), World Steel in Figures 2019. https://www.world steel .org/en/dam/jcr:96d7a 585-e6b2-4d63-b943-4cd9ab621a 91/World %2520Steel%2520i n%2520Figure s%25202 019.pdf.

Yamaji K, Matsuhashi M, Nagata Y, Kaya Y (1991). An integrated system for CO2/ energy/GNP analysis: case studies on economic measures for CO2 reduction in Japan. Workshop on CO2 Reduction and Removal: Measures for the Next Century. 19–21 March 1991. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Yamamoto H, Yamaji K (1996). Development of a global land use and energy model (GLUE) considering biomass flow.

Yu HJJ, Popiolek N, Geoffron P (2016). Solar photovoltaic energy policy and globalization: a multiperspective approach with case studies of Germany, Japan, and China. Prog Photovoltaics ResAppl 24:458–476. https ://doi.org/10.1002/pip.2560

Final Report

Submitted by
Asian Institute of Technology, Thailand
PI: Joyashree Roy
Bangabandhu Chair Professor

Submitted to
The Research Institute of Innovative Technology for the Earth (RITE), Japan

Energy **D**emand changes **I**nduced by **T**echnological and **S**ocial innovations (EDITS)-AIT Project Report- Phase II

Project period: June 1, 2021-March 31, 2022

Report period: June 1, 2021-February 28, 2022

Asian Institute of Technology

Contents

Deliverables 3

1. Participation by PI (and team members / nominee) and contribution in virtual workshops/seminars 3

2: Obtaining data and Information for EDIT report 5

Tasks accomplished 5

1. Gathering information through research network in South Asian region to understand State of the knowledge in energy demand side in South Asian Region 5

2. Building and strengthening the research network in South Asian region and capacity among researchers to conduct systematic search for data and literature for EDITS 8

3. Publications/submitted to journals with acknowledgement to EDIT 8

Team research and contribution foreseen in the EDITS work in 2022 9

Annexures 12

Deliverables

1. **Participation by PI (and team members / nominee) and contribution in virtual workshops/seminars**

1.1 Participation in IIASA's Quarterly workshop/working groups

a. Joyashree Roy and her team (Dr. Indrajit Pal (AIT, Thailand), Dr. Joyee S. Chatterjee (AIT, Thailand), Dr. Nandini Das (JU, India) and Shreya Some (JU, India) actively participated in two Quarterly workshops held in June 2021 and September 2021 and have actively contributed to the discussion sessions.

b. Joyashree Roy was a speaker in the Panel Discussion: Energy transition Towards a Sustainable Future in Asia, organized by IIASA and National Natural Science Foundation of China (NSFC), in partnership with Iran National Science Foundation (INSF), Japanese Committee for IIASA, National Research Foundation of Korea (NRF) and Technology Information, Forecasting and Assessment Council (TIFAC) are co-organizing IIASA Regional Conference "Systems Analysis in Asia" in Beijing, China held on 20-22 October 2021.
Summary of the session: Energy Transition towards a sustainable future in Asia was the topic of presentation. Main message was when a major transition needs to start in this decisive decade of 2010 developing countries have options to explore multiple ways how energy demand can be avoided, improved and shifted to avoid on a high emission development pathway. Although there are evidences that electricity intensity is falling in some large developing country like India but the case is not uniform in the region as Bangladesh has potential for improving energy efficiency. But For country like India major shift need to happen in power generation to achieve low emission scenario. Clean power generation can help in more electrification of mobility sector and can help in urban air pollution which data from pandemic related shut down period revealed in Indian city. For Bangladesh there are some major barriers which need to be overcome by enabling policy reforms. In Bangladesh to achieve sustainable energy transition and SDGs disaster resilient framework data, capacity building and policy issues emerged as major sensitive intervention points.
The conference recording is available in YouTube here:
https://www.youtube.com/watch?v=dMyW2L3eNTI
Pictures from the event are attached in Annexure I

c. Joyashree Roy was the Moderator in the RITE-IIASA side-event on EDITS at COP26 held on 11 November 2021.
(https://previous.iiasa.ac.at/web/ece/211111_EDITS_COP26.html)
Summary of the session:
Energy Demand and how it can contribute to mitigation. 100 plus scientists are participating in this research community for exploring Low demand futures. Expert speakers were of the opinion that it is possible to have a better future world with less energy demand. In that world there will be provision for enough energy to meet decent living aspirations of all world population. Such a future world will be focused more on innovations that enable people/end users to access technologies that are modular, improves faster with cost improvements due to fast diffusion and learning. It is expected that such future human society will be managed more by digital technology, artificial intelligence so that demand can be managed better cutting across sectors, blurring the sector boundaries and helping in optimisation of the subsystems and systems in terms of resource use, reducing waste. So, this group is trying to establish scientifically a possible future scenario which is Fundamentally different than what we are living in now.
Pictures from the event and report back slides attached in Annexure II

d. Joyashree Roy and her team participated in the Annual EDITS Workshop 2021, held in December 2021 and have participated in the discussion and social events.

e. Joyashree Roy participated in focused discussions on the Industry and the Data Working Groups in January 2022.

1.2 Participation in other relevant virtual workshops/seminars

a. Joyashree Roy was invited to deliver a lecture on “Co-benefits of Climate Policy in Asian Regions”, in the International Autumn School: “Climate Policy and Energy System Transformation: New Opportunities and Challenges of the Consideration of Co-Benefits” organized by Technical University Bergakademie, Freiberg, Germany on 13 September 2021.

b. Joyashree Roy participated in the webinar “COP26 – Where do we go from here: AIT Faculty Experts Analysis”, held on 22 November 2021 as a Panellist (Energy)(https://www.ait.ac.th/2021/12/cop26-where-do-we-go-from-here-ait-faculty-experts-analysis/)
Pictures from the event attached in Annexure III

c. Joyashree Roy participated in the webinar "21st Century Economy, Climate, Energy and Social Transformations: Bangladesh Perspective", held on 6 December 2021 as a Resource Person.
Summary of the session:
The fast-growing economies like Bangladesh has scope for both supply side and demand side innovation to reduce emissions during the fast growing phase. While supply side can look for cleaner sources keeping just transition in focus demand side inefficiencies can be reduced by technology uptake and enabling policy consideration which tries to build resilience of energy infrastructure and creates new job opportunities.

2: Obtaining data and Information for EDIT report

a. Gathering information through research network in South Asian region.
b. Building and strengthening the research network in South Asian region and capacity among researchers to conduct systematic review of literature for EDITS project/report.
c. Thematic research groups formed: India, Bangladesh to decide about academic output, method, rapid systematic literature review, study design and data need/source identified. Explore possibility/scope of involving policy/decision makers within the region/countries.
d. State of the knowledge in energy demand side in South Asian Region

Tasks accomplished

1. **Gathering information through research network in South Asian region to understand State of the knowledge in energy demand side in South Asian Region**

   a. **Quick feedback on quantitative data availability status (two countries: India and Bangladesh)**

End-use Sector	Brief description of data	Data availability (types and years)
India		
Household/ Residential	Fuel consumption expenditure: Firewood, LPG, Electricity, Kerosene and Transport fuel (both rural and urban)	Secondary data available at 5 years interval from 2004 Primary survey data for smaller geographic region available with researchers on specific demand change due to policy, market incentive with some data on

		appliance ownership, floor area by building type
Power generation	Consumption of energy by primary and secondary carrier type: Coal, Lignite, Natural Gas, Crude oil, Electricity, Petroleum products	Available from 1990 onwards (1973 onwards possible from individual researchers)
Power demand	Load	Hourly, Monthly for various regions and national level (at least for five years)
Industry	Consumption of energy resource: Coal, Lignite, Natural Gas, Crude oil, Electricity, Petroleum products	Available from 1990 onwards (1973 onwards possible from individual researchers) (industry group/aggregate), product specific production data available can be considered as representation of demand
Transport	Consumption of energy resource: Coal, Lignite, Natural Gas, Crude oil, Electricity, Petroleum products	Available from 1990 onwards (earlier also possible but would need some check and cleaning) (vmt and pmt some available from survey based data, need better search),
Agriculture	Consumption of energy resource: Coal, Lignite, Natural Gas, Crude oil, Electricity, Petroleum products	Available from 1990 onwards
Services sector (e.g., health/water supply. at the aggregate level)	Consumption of energy resource: Coal, Lignite, Natural Gas, Crude oil, Electricity, Petroleum products	Available from 1990 onwards
Mining & Quarrying	Consumption of energy resource: Coal, Lignite, Natural Gas, Crude oil, Electricity, Petroleum products	Available from 2004 onwards

Bangladesh		
Household/ Residential	Fuel consumption expenditure: aggregate, biomass and electricity (both rural and urban)	Secondary sources, Primary survey based data for smaller geographic region available with researchers on specific demand change due to policy, market incentive with some data on appliance ownership
Power generation	Consumption of energy by primary and secondary carrier type: Coal, Lignite, Natural Gas, Crude oil, Electricity, Petroleum products	Available from 1990 onwards (1973 onwards possible from individual researchers)
Industry	Consumption of energy resource: Coal, Natural Gas, Crude oil, Electricity, Petroleum products	Available from 1990 onwards
Transport	Consumption of energy resource: Coal, Lignite, Natural Gas, Crude oil, Electricity, Petroleum products	Available from 1990 onwards
Agriculture	Consumption of energy resource: Natural Gas, Crude oil, Electricity,	Available from 1990 onwards
Services sector (e.g., health/water supply. at the aggregate level)	Consumption of energy resource: Coal, Lignite, Natural Gas, Crude oil, Electricity, Petroleum products	Available from 1990 onwards

b. Literature availability through systematic search: Existing literature on Energy demand in South Asia

i) First set of focused keyword search for South Asia has been completed

ii) Reading of literature is in progress

iii) Key observations (in the reporting period):

- Demand for electricity varies with household size, income and urban or Rural
- There lies a difference between energy consumption pattern of rural-urban sector
- Shift to electricity is a major trend and challenge in energy demand management

- Price as a significant tool of energy demand management

2. **Building and strengthening the research network in South Asian region and capacity among researchers to conduct systematic search for data and literature for EDITS**

   a. PI is teaching One 3 credit course and one 1 credit course at AIT at the Programme on Sustainable Energy Transitions :
      - Energy demand and Pricing (3 credit course)
      - Energy Technology, Transition and Sustainability (1 Credit)

   b. A Focused Research centre initiated at AIT under the School of Environment, Resource and Development (SERD) on "South and South East Asia Multidisciplinary Applied Research Network on Transforming Societies in Global South" .

   c. Four Thematic working groups formed with group leads from AIT and working with researcher/s to decide about academic output, method, rapid systematic literature review, study design and data need/source identified. Explore possibility/scope of involving policy/decision makers within the region/countries.

      1. Quantitative modelling, data, establishing policy links (Joyashree Roy (AIT) and Sakib Bin Amin (Bangladesh))
      2. Infrastructure, disaster and energy demand (Indrajit Pal (AIT) and Sheikh Tawhidul Islam (Bangladesh))
      3. Micro Grid a new technological innovation and social embedding and energy demand implications (J.G Singh (AIT) and Debalina Charavarty (India))
      4. Energy Demand Narrative as is appearing in public discourse (Joyee S Chatterjee (AIT) and Purbasha Auddy (India)

3. **Publications/submitted to journals with acknowledgement to EDIT**

   a. **One article published**

   Title of the paper: Solar Microgrids in Rural India: A Case Study of Household Benefits

   Abstract: This study evaluates the benefits that rural households in India derive from dedicated solar microgrid service systems. A case study was conducted in Lakshmipura-Jharla, Rajasthan, a village in western India with significant potential for producing solar energy. In 2013, a private investor set up a solar microgrid in the village and distributed energy-efficient appliances. Its goal was to give poor households access to modern energy services. The study data were collected through a survey conducted among randomly selected households in the village. The survey found that such an electricity provision service had multidimensional benefits: flexible use of the energy service, more effective time allocation among women, more study time for students, improved indoor air quality, and safer public places. Given the initial unmet demand for modern energy in the village, technological interventions supported by policy has helped to expand consumption possibilities and new demand for services has emerged. The household-level frontier rebound effect is estimated to be more than 100%, reflecting a one-and-a-half times increase in the demand for illumination services among rural households. Frontier rebound effect estimates help quantify the benefits of solar microgrids and energy-efficient appliances for households in rural areas. The results of this study are consistent with existing literature that suggests that efficient appliances and access to electricity will increase the energy demand manifold and satisfy the growing and largely unmet demand for energy.

Full paper attached in Annexure VII

b. **Two articles submitted to Edited volume and peer reviewed journal**
ii.a) Paper 1 title: e-mobility for a sustainable world: unavoidable automobility and global south-north perspectives (in edited volume)
ii.b) Paper 2 title: Food waste reduction and dietary choice: exploring links to Sustainable Development Goals (in peer reviewed journal and received reviewers' comments for revision)

Team research and contribution foreseen in the EDITS work in 2022

Team
Team name: EDIT-AIT

Team leads and lead researchers:
Joyashree Roy (joyashreeju@gmail.com; joyashree@ait.asia), Indrajit Pal (indrajit-pal@ait.asia), Joyee S Chatterjee (joyeec@ait.asia), J. G. Singh (jgsingh@ait.asia), Sakib Bin Amin (sakib.amin@northsouth.edu), Sheikh Tawhidul Islam (s.t.islam@juniv.edu)

Docs/Post docs: Anil Kumar (st121810@ait.asia), Shreya Some (ayerhs7891@gmail.com), Purbasha Auddy (pauddy@gmail.com), Hasan Mahmud (hmplus02@gmail.com)

Workplan directly related to EDITS
Areas of interest and foreseen contribution:

1. Get research partners/researchers from Nepal, Bhutan, Sri Lanka, Pakistan, Thailand in thematic areas identified in Phase 1 and 2 to assess country specific data availability (as done for Bangladesh and India) and literature availability in SE region (as done in phase 1 and 2 for SA region)
2. Complete review of data and literature for South Asian region to comprehensively and collectively decide regionally on data gap and literature gap and assess various quantitative comparable analysis that can be done for the region
3. Demand side literature and modelling studies (search complete) as exist in the South and South East Asia regions and make some progress with quantitative analysis to assess demand side potential in the region/country
4. Energy infrastructure - expected expansion path, disaster resilience and adaptation and energy demand implication
5. Engaging more with policy/decision makers to understand regional focus and barriers on demand side.
6. Data comparisons in the region, start of model application with data compiled for at least one country, for example for Bangladesh developing demand reduction through energy efficiency pathway for Bangladesh relative to 2018/2019 and compare with NDC and other pathways as emerging from policy documents.
7. Microgrid and EV expansion in SA and SE Asia and impact on electricity demand
8. Review of Narrative that is emerging on demand side in the regional context in popular newspaper communication media
9. Organise a workshop/conference panel in the region on EDIT

Interest to participate in IIASA-WG(s):
Industry (Joyashree and Shreya), Building (Joyashree and Shreya), Transport (Joyashree and Shreya), Data (Joyashree and Shreya), Protocol (Joyashree), Narrative (Joyee and Purbasha), Synthesis (Joyashree)

The scientific goal/research question for 2022

- What is driving the sector/service specific demand most in the region and how is decoupling emerging at the country level and regional level?
- To what extent infrastructure choice will create committed demand and emissions in the region?
- How the popular newspaper media based narratives is impacting transition to low energy demand future?

- What are the emerging modular power supply and transport sector technologies emerging in the region with implication for energy demand and multiple SDG co-benefits ?
- What are the most relevant technologies for increasing energy demand side flexibility with increasing renewable energy penetration in the region?

Foreseen product(s) of 2022

- Bottom-up country specific (at least for India and Bangladesh using same method) reference scenario and sources of relative/absolute decoupling in the region.
- Systematic review of literature for the as publishable article
- Preliminary insights on infrastructure-disaster resilience-adaptation and energy demand implication
- Micro grid, EV, policy and techological innovation including increasing digitization and energy demand assessment (country case study)
- Popular media Communication and energy demand (a possible publishable Paper)
- Special issue Journal with perspectives/research from the region

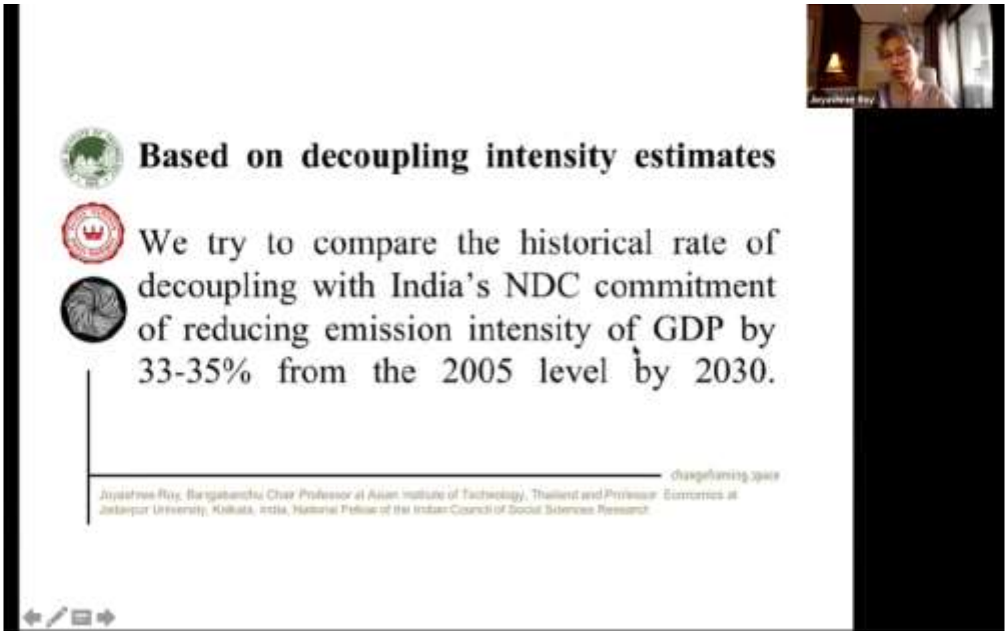
Methods to be used: (under consideration)

- Decomposition method based bottom-up scenario analysis and pathway development
- IDEEA (Indian Zero Carbon Energy Pathways) Model based results to build on demand side flexibility
- Systematic literature review
- Econometric models
- Geospatially linked models

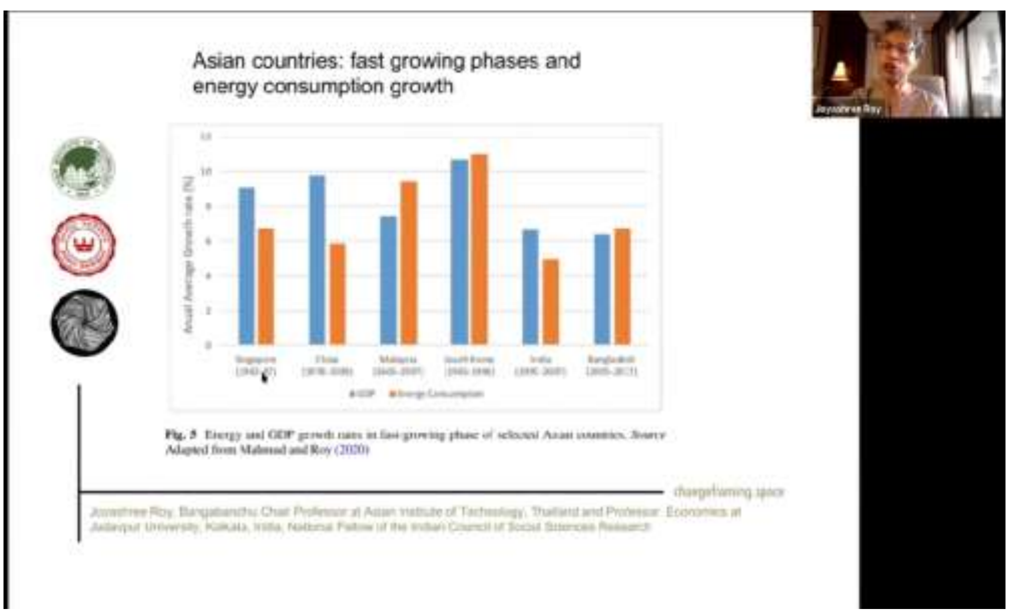
Timeline: 2022 April-2023 March

Annexures

Annexure I



Joyashree Roy discussing about decoupling intensity



Joyashree Roy discussing about energy consumption growth during the fast growing phases of Asian countries

Annexure II

Moderator- Joyashree Roy and the Speakers of the COP26 event

Report back slides

Connecting science and policy: COP26 report

Session 1, EDITS Annual Meeting
9-10 December 2021

Joyashree Roy

Please consider the environment before printing this slide deck
Icon from all-free-download.com Environmental icons 310835, by BSGstudio, license CC-BY

Side-event in numbers

- Date: 11.11.2021, 13:00-14:30 (GMT)
- Place: Japan Pavilion (on site); YT (live streaming), zoom (participation)
- Recording (on demand):
  - ⇒ Ministry of Environment (Japan)
  - ⇒ RITE (https://www.rite.or.jp/system/en/events/2021/11/cop26_1.html)
  - ⇒ IIASA (dedicated webpage under EDITS)
- Number of participants: 50+?
- Number of presentations: 6 + one panel
- Content: low energy demand scenarios and their climate, development and technology relevance

Side-event programme

Energy demand changes induced by technological and social innovations and the model intercomparison (Japan Pavilion)

At this event, the importance of technological and social innovations in the energy demand sector, and the potential achievements of a low energy demand society, that can be induced by the innovation in the significant reduction of greenhouse gas emissions and sustainable development in the world was discussed. This seminar also introduced the research scope and provisional analyses/evaluations of the EDITS project.

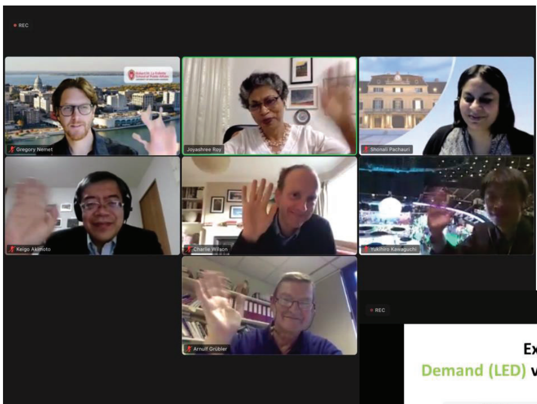
Speakers/Panelists

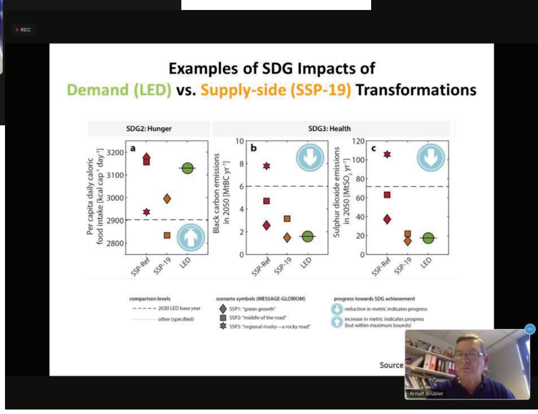
- Yukihiro Kawaguchi	Director, Global Environmental Affairs Office Industial Science and Technology Policy and Environment Bureau Ministry of Economy, Trade and Industry (METI)
- Keigo Akimoto	Research Institute of Innovative Technology for the Earth(RITE)
- Arnulf Grübler	International Institute for Applied Systems Analysis (IIASA)
- Charlie Wilson	University of East Anglia (UEA), Tyndall Centre for Climate Change Research
- Shonali Pachauri	International Institute for Applied Systems Analysis (IIASA)
- Greg Nemet	University of Wisconsin-Madison, La Follette School of Public Affairs, Wisconsin Energy Institute

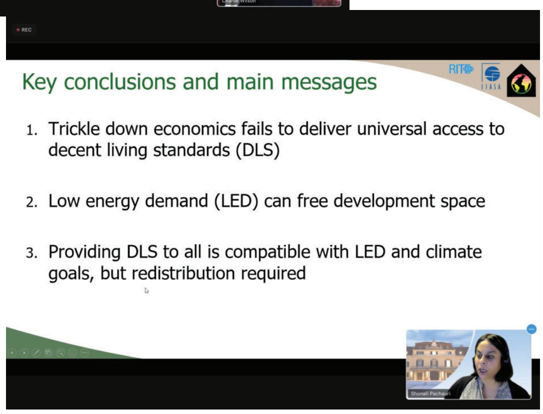
Moderator

- Joyashree Roy	Asian Institute of Technology (AIT)

Side-event in pictures







Side-event main mood of the discussion

- Energy Demand and how it can contribute to mitigation
- 100 plus scientists are participating in this research community for exploring Low demand futures
- Yukihiro Kamaguchi Director of the Global Environmental measures office in METI shared the mood of COP26 and he was in action zone when we were online.
- His main message was that carbon neutrality is global goal but will be reached in variety of ways depending on context and he mentioned about relevance of EDIT project in the current heavily focused mitigation discourse around supply side interventions. How green transformation and Digital transformation can help in the process.
- Keigo Akimoto emphasized how Model development , Integration with SD dimensions and policy need to be focused while looking into demand side

5

Side-event main mood of the discussion

Arnulf 's main message was It is possible to have a better future world with less energy demand

Addressing the equity issue Shonali had to say in that world there will be provision for enough energy to meet decent living aspirations of all world population

Greg put forward his perspective that such a future world will be focused more on innovations that enable people/end users to access technologies that are modular, improves faster with cost improvements due to fast diffusion and learning

Charlie's main message was that future human society will be managed more by digital technology, artificial intelligence so that demand can be managed better cutting across sectors, blurring the sector boundaries and helping in optimisation of the subsystems and systems interms of resource use, reducing waste.

So this group is trying to establish scientifically a possible future scenario which is Fundamentally different than what we are living in now

6

Side-event main mood of the discussion

During question answer session it became clear that

- to explain what would be the metric for measuring the "better future world?" Because still the fundamental driver of economic growth paradigm within which the world functions is driven by "More is better"/"non declining consumption philosophy".

Clearly it came out we need more robust indicators which represents human wellbeing going beyond economic wellbeing.

- if energy consumption for decent living for all has to increase within carbon budget? Where and in what magnitude consumption need to come down and how to drive such balancing change ?

Side-event main mood of the discussion

- What is needed is speed of change and scale of change what cab drive such change?? Market mechanism? Non market mechanism? An ideal mix? Energy efficiency has helped in reducing energy need per output production but per capita energy need has not declined so how to manage the rebound effect?

- transformative change through digital innovation is inevitable. But how inevitable rise in demand for energy e.g., in data centres can be managed?. Secondly this is happening in a world which is digitally divided in terms of access, capability, capacity. So in this process of transformation how much of concern should this be and How do avoid growing inequity from the very beginning?

- Even if all energy sources becomes clean energy still there will be need for low energy demand future to explore to be within limits of planetary boundary

Side-event main mood of the discussion

However, many studies show the importance of demand-side strategies in transition to low-carbon/ net-zero societies. This concept is missing and/or in the low priority in the science-policy interface and policy-makers discussions.

How can we bring these important messages (e.g. through socio-behavioral changes, service provisioning) to the level of policy-makers as politically feasible, easy implemental strategies?

Side-event main mood of the discussion

Lowering energy demand is commonly perceived (wrongly) by policymakers as being about restricting activity, 'interfering' in people's lifestyles, and so negatively impacting wellbeing.

This is why LED and similar analyses in the EDITS community and beyond is so important - to build, strengthen, and communicate the evidence that lowering energy demand can improve wellbeing with significant benefits for climate and SDGs.

Thank you very much for your attention!

As a partner institution in the EDIT project Asian Institute of Technology (AIT) is focusing on Energy demand changes in South Asia and South East Asian Countries Induced by Infrastructural, Technological, Behaviourial and Policy changes.

EDITS is an initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA), and funded by Ministry of Economy, Trade, and Industry (METI), Japan.

Joyashree Roy
Bangabandhu Chair Professor
Asian Institute of Technology Affiliation
Thailand
joyashree@ait.asia /joyashreeju@gmail.com
https://iiasa.ac.at/web/home/research/researchPrograms/Energy/Research/EDITS/EDITS.html

Annexure III

Ecology, Economy and Society–the INSEE Journal 4 (2): 65-93, July 2021

RESEARCH PAPER

Annexure VII

Solar Microgrids in Rural India: A Case Study of Household Benefits

Debalina Chakravarty[1] and Joyashree Roy[2]

Abstract: This study evaluates the benefits that rural households in India derive from dedicated solar microgrid service systems. A case study was conducted in Lakshmipura-Jharla, Rajasthan, a village in western India with significant potential for producing solar energy. In 2013, a private investor set up a solar microgrid in the village and distributed energy-efficient appliances. Its goal was to give poor households access to modern energy services. The study data were collected through a survey conducted among randomly selected households in the village. The survey found that such an electricity provision service had multidimensional benefits: flexible use of the energy service, more effective time allocation among women, more study time for students, improved indoor air quality, and safer public places. Given the initial unmet demand for modern energy in the village, technological interventions supported by policy has helped to expand consumption possibilities and new demand for services has emerged. The household-level frontier rebound effect is estimated to be more than 100%, reflecting a one-and-a-half times increase in the demand for illumination services among rural households.

access to electricity will increase the energy demand manifold and satisfy the growing and largely unmet demand for energy.

Keywords: Modern Energy Services; Energy-efficient Appliances; Frontier Rebound Effect; Rural Household; Solar Microgrid.

1. INTRODUCTION

The Indian government has implemented several initiatives to promote and accelerate the scaling up of rural electrification and efficient appliances use through new institutional arrangements and policy support. Solar microgrids are considered an alternative service delivery model to grid electricity in remote villages that either do not have grid connectivity (Thirumurthy *et al.* 2012; World Bank 2008) or where it is neither feasible nor cost-effective. While on an average grid electricity is less expensive than off-grid options, the levelised cost per kWh of grid extension rises steeply beyond a certain distance from the central facility (World Bank 2010; Bruckner *et al.* 2014). Therefore, microgrids are seen as a cost-effective solution for rural electrification in India (Venkataraman and Marnay 2008). It is important to scrutinize past experiments for lessons that may help us better understand which policy interventions will aid the speedy advancement of such initiatives and boost the demand for such electricity among rural households. This can help us assess the microgrid capacity required and how quickly supporting infrastructure needs to be built. The first mention of solar microgrids at the policy level in India can be found in the Decentralised Distributed Generation (DDG) scheme proposed by the Ministry of Power as part of the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY), 2005. This programme's goal was to electrify villages where grid connectivity is neither feasible nor cost-effective and to supplement power provision in areas where the grid supply is available for less than six hours a day. In 2014, rural electrification gained momentum with Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY) and the Integrated Power Development Scheme (IPDS), which emphasized solar energy and introduced a smart metering system to enhance end-user access. In addition, the Indian government also designed a policy instrument for subsidy allocations to encourage private investors to enter the electric services market through private microgrid systems in rural areas. A microgrid is an integrated, local system that generates electricity and transmits it to end-users (residential and commercial users) within a limited geographical region. A microgrid operating on renewables like biomass, wind, and solar photovoltaic (PV) technology can help increase power quality, reliability, efficiency, and sustainability (Kaundinya *et al.* 2009). The argument in favour of renewable energy-based microgrids and energy-efficient appliances is mostly driven by the scarcity of non-renewable fossil fuel–based energy and its impact on human health and climate change. Microgrid systems also provide more reliable electricity, as outages or interruptions in supply can be quickly identified and corrected. Additionally, transmission and distribution costs are low with microgrids and very little electricity is lost during transmission (Hirsch *et al.* 2018).

In India, a large number of rural households without access to grid electricity or any other reliable energy source depend on firewood or fossil fuels to meet basic energy needs like cooking and illumination. The detrimental health and environmental impacts of these fuels are well known (Johnson and Chiang 2015; Parikh 2011). Therefore, reliable access to cleaner energy sources is crucial in terms of the environment and climate change mitigation (Millward-Hopkins *et al.* 2020; World Bank 2008; GEA 2012; Alliance for Rural Electrification 2011); in addition, it stands to contribute towards meeting multiple Sustainable Development Goals (SDGs) by improving households' health and quality of life (UNEP 2017). However, it is difficult to estimate the level, pattern, and growth of total energy demand at the community scale. This makes it difficult for private companies to invest in microgrids (Williams *et al.* 2015; Wang and Huang 2014). Therefore, to plan and design better solar microgrids, it is essential to understand the demand for such grids and how they benefit users and the community.

Contemporary literature on energy demand indicates that when a certain energy service becomes more technically efficient, energy demand in total increases and not just for that particular energy service. This is called the "rebound effect" (Chakravarty *et al.* 2013; Sorrell and Dimitropoulos 2008; Vikstrom 2008; Greening *et al.* 2000; Saunders 2000; Roy 2000). This happens because users interpret energy efficiency increases as the increased availability of energy services at the same price; in other words, as the effective prices of energy services reduce, consumers respond by demanding more of that energy service. The literature suggests that the rebound effect can be partial or full or may backfire (Roy 2000; Roy *et al.* 2013; Lin and Liu 2013a; Lin and Liu 2013b; Lin and Liu 2015; Druckman 2011; Saunders 2000; Sorrell 2009). But these outcomes are dependent on whether the demand increase is relatively lesser, equal to, or greater than the magnitude of energy efficiency improvement.

The frontier rebound effect is a special case that the literature describes as an increase in the total energy demand due to improved efficiency as a result of a technological innovation within a particular energy service—such as in the case of fuel-efficient cars in mobility services or LED bulbs in illumination services (Jenkins *et al.* 2011; Saunders 2013). The literature also shows, through empirical studies, that when one energy service becomes cheaper and more easily available, consumers devise new and innovative ways to use that energy (Saunders and Tsao 2012), which leads to an increase in the total energy demand. This is an extreme case of the rebound effect caused by the increased availability of opportunities for energy consumption and discovery of unforeseen opportunities for substitution. This increased consumption can have a significant impact on economic activities. This phenomenon is often seen in developing countries with constrained energy access and a lot of unmet demand (Roy 2000; Chakravarty *et al.* 2013). The presence of such an effect indicates that unmet demand falls faster with an increase in the social well-being of the beneficiary (Saunders 2013; Freeman 2018).

This case study explores solar microgrids as an alternative electricity service provision system in human settlements with high unmet demand. The study also examines the role of energy-efficient appliances in such environments. The case study was based on the village Lakshmipura-Jharla in India, where a single solar microgrid system was set up by a private investor. The details of the study are covered in Section 2. Section 3 discusses the estimated frontier rebound effect based on the available data. Section 4 presents a discussion of the results, and Section 5 provides concluding remarks.

2. THE CASE STUDY SITE

The first commercial-scale solar microgrid (and energy-efficient appliances programme) was set up in 2012–2013 as a private–public partnership (PPP). Gram Power (a private solar microgrid company based in India) set up its pilot project in the village Lakshmipura-Jharla in the Tonk district of Rajasthan, which was unconnected to the grid. High levels of solar irradiance[3] made it an apt location for the project, and in March 2012, a microgrid with a capacity of 2kW was set up. One of the authors visited the village in July 2013. The study site is located 1 km from the relatively well-connected village of Khareda, which, in turn, is located 150 km from Rajasthan's capital city, Jaipur.

In 2003–2004, a start-up introduced the '*jugnu*' system, wherein individual solar lanterns were distributed to village households at the subsidized price of ₹7,000 ($111)[4] per unit. However, these lanterns could only provide four

[3]Solar irradiance is a measure of the solar radiation (power per unit area on the earth's surface) produced by the sun in the form of electromagnetic radiation (IPCC 2007).

[4]All conversion in this study is calculated using the exchange rate: USD 1 = INR 63 (average exchange rate for the year 2013).

hours of light a day, leading to high unmet demand. Then, in 2012, a private company set up a solar microgrid in the village and provided households with smart meters that allowed them to access 24x7 uninterrupted electricity supply. They also provided households with two energy-efficient 14 W or 16 W compact fluorescent lamp (CFL) bulbs. At the time, the cost of a bulb was around ₹70 when bought in bulk. The bulbs were distributed at a subsidized price of ₹15 per bulb as per the Bachat Lamp Yojana (2012) to microgrid-connected households. The private company installed and operated the microgrid in collaboration with the state renewable energy board under the Ministry of Power and the Development Impact Lab (DIL), University of California, Berkeley, USA, provided scientific knowledge. Private investors provided 80% of the total cost of installation in return for import duty exemption for certain components in the system. The remaining 20% was contributed by the Indian government under the Jawaharlal National Solar Mission (2010). The objective of the PPP model was to leverage private investment to expand the supply capacity and meet new energy demand through renewable sources such as solar (World Bank 2008; GEA 2012; Alliance for Rural Electrification 2011; UNEP 2017) (Table 1).

Unlike solar lantern systems that are meant for use within the home, microgrids provide uninterrupted power service 24x7 at a community level. The latter provides flexibility to end-users in their choice of appliances and has better social, environmental, and economic benefits compared to lanterns while reducing costs by utilizing economies of scale (Table 1). Despite these well-established benefits, there exist some practical barriers to solar microgrids—for example, the poor availability of skilled technicians, lack of timely maintenance and monitoring, etc. (Fowlie *et al.* 2018). In our case study, we found that the private partner was committed to overcoming these known barriers.

Table 1: Solar Microgrid Systems: Benefits and Barriers

Benefits and barriers					References
Actors		**Producer & distributor**	**End-user**	**Other**	
Benefits	**Economic**	Low cost of raw energy, reduces transmission loss	Planned electricity consumption	Local employment generation, economic development	Dieckmann 2013; Chen *et al.* 2011
	Social		Improvements in health, study time, cooking time, communal activities, etc.		Fowlie *et al.* 2018; World Bank 2008
	Environmental	Less greenhouse gas (GHG) emissions, less local pollution, less non-renewable energy use			Dieckmann 2013; Kamel *et al.* 2015; Molina and Mercado 2010; Vachirasricirikul and Ngamroo 2011
Barriers		Lack of improved technologies, efficient monitoring systems, and expertise	Higher electricity tariffs	Regulatory barriers	CEA 2012; Chakravarty 2016

Source: Compiled by authors from various sources

3. END-USER BENEFITS OF THE SOLAR MICRO-GRID: ESTIMATION OF THE FRONTIER REBOUND EFFECT

Estimating the frontier rebound effect can show how an increase in the efficiency of any appliance changes end-user behaviour and affects their total energy consumption (Chakravarty *et al.* 2013; Sorrell and Dimitropoulos 2008; Vikstrom 2008; Herring 1998, 2006; Greening *et al.* 2000). Khazzoom first mentioned this effect in the early 1980s when discussing household energy consumption (Wei 2010; Sorrell 2007; Allan *et al.* 2008; Allan *et al.* 2006; Herring 2006; Saunders 2000a; Khazzoom 1980). The literature shows that end-users respond in the same way to energy efficiency as they do to a decrease in energy prices (Sorrell and Dimitropoulos 2008). Therefore, the rebound effect is equivalent to the percentage change in the demand for energy services, i.e., the perceived reduction in price due to efficiency improvements in energy-using appliances (Berkhout *et al.* 2000; Sorrell 2007; Saunders 2005; Sorrell and Dimitropoulos 2008; Frondel *et al.* 2008; Binswanger 2001). The change in energy service demand due to a change in perceived price can be greater than 100% in magnitude, which is identified as the frontier rebound effect. Energy efficiency gains create opportunities for undertaking new economic activities using the same supply of appliances. In parallel, the demand goes up for new energy-embedded products (Jenkins *et al.* 2011; Saunders 2013). For example, Tsao *et al.* (2010) analysed 300 years' worth of historical data about lighting appliances and fuel-use from three continents and discovered that despite advances in appliances and fuel-use efficiency, energy consumption has been increasing.

Evidence from past studies in India shows a widely varying rebound effect (Roy 2000; Roy *et al.* 2013; Chakravarty and Roy 2017). There was super-conservation or a negative rebound among sufficiently conscious urban consumers (Chakravarty and Roy 2017); however, "backfire" (Roy 2000; Roy *et al.* 2013) was more likely in households with unmet energy demand. Sorrell (2007; 2009) observed that backfire due to the frontier rebound effect is most likely to occur with general-purpose technologies as they usually have a wide scope for improvement and elaboration. These general-purpose technologies complement existing and potential new technologies, particularly when energy efficiency gains can be made at an early stage in the development and diffusion of the technology. The opportunities created by these technologies can have significant, long-term effects on innovation, productivity, and economic growth; the subsequent increase in economy-wide energy consumption further increases these effects.

To understand the frontier rebound effect of the microgrid system, we compared the benefits accrued to households from solar microgrids against a benchmark situation, i.e., households' illumination consumption via domestic solar lantern systems. To estimate the frontier rebound, we used the following equation (1) (Roy 2000; Saunders 2012, 2013; Freeman 2018):

$$Frontier\ Rebound = \frac{\%\ change\ in\ energy\ service\ consumption}{\%\ change\ in\ energy\ service\ price} = \frac{\Delta q}{\Delta p} \times \frac{p_t}{q_t} = \frac{q_n - q_0}{p_n - p_0} \times \frac{p_0}{q_0} \ldots\ldots eq(1)$$

Where, q represents energy service consumption and p represents the price (implicit) of the energy service.

Specifically, $\Delta q = q_n - q_0$

Where, q_n is the energy service consumption at the current time point and q_0 is the energy service consumption at the base time point.

Again, $\Delta p = p_n - p_0$

Where, p_n is the energy service consumption at the current time point and p_0 is the energy service consumption at the base time point.

The rebound was estimated for the illumination service as in this case study efficient appliances were introduced for lighting purposes only. The impact of electricity access could be estimated as the frontier rebound effect using equation (1). Thus, we were able to estimate the total increase in energy service demand resulting from the energy access intervention by comparing the pre-microgrid and post-microgrid situation. In the rebound estimation, the price mentioned in equation (1) represents the estimated price per particular "service" (e.g., illumination/cooking/heating). To estimate these prices per service, we used service-specific expenditure data. We also estimated the expenditure both before and after the introduction of the solar microgrid. We estimated the cost of a domestic solar lantern system using annualized monetary expenditures (*E(q)*) divided by the quantity of consumption (*q*) (Filippini and Pachauri 2004). *E(q)* is the total annualized cost of consumption derived from the capital cost and operating cost (including maintenance) borne by households. Capital cost includes investment and interest charges. To estimate what part of the unit cost can be attributed to capital investment, we used the method suggested by Culp (1979).[5]

5

$$E(q) = total\ annualised\ cost$$
$$= annualised\ capital\ cost + annual\ operation\ cost + annual\ maintenance\ cost$$

Here, $annualised\ capital\ cost = first\ cost \times annualised\ factor$

$$and\ annualised\ factor = i + \frac{1}{\{(1+i)^t - 1\}}\ (*)$$

Data were collected from users who owned domestic solar lantern systems. The solar microgrid expenditure and energy consumption data were directly collected from the energy meters and payment receipts. The number of households and the names of the heads of households were first collected from the village panchayat office; then, every alternate house from the village was selected for the survey. If the selected house was vacant, or its members were unavailable or unwilling to participate in the survey, the next house was selected. Each household was given the option of exiting the survey at any time to minimize bias and erroneous responses. In conducting the survey, standard survey ethics were followed. Consent was taken from each of the stakeholders (the educational institute based in the US, private start-up, households) before the purpose of the study was explained.[6]

A key aspect of the survey was collecting data on the energy service demand pattern of households before and after they had access to the solar microgrid and efficient lamps, and how these corresponded to their energy bills. Both types of information were collected through direct interviews based on a pre-formatted, tested, and piloted questionnaire. Since the appliance usage patterns of households influence electricity demand, the technical specifications of the appliances were very important in this study. Therefore, the questionnaire[7] also collected information about the types of appliances used in households, the number of appliances, their specifications, wattage consumption, usage time in both summer and winter, whether they were energy-efficient or not, and their initial cost. Apart from this, the questionnaire also had qualitative questions on how households perceived the impact of electrification.

4. RESULTS AND DISCUSSION

The total population in the study village was approximately 100 people living in 22 households. The average family size was roughly five members. Eleven households responded to the interview. The village is situated on the banks of the river Banas, which forms a moderately rich fertile plain.

Where, *t* is the operating time period/lifetime of the equipment and is considered as 10 years for this calculation, and *i,* is the rate of interest and is assumed to be 8% for the present calculations, given the then prevailing market interest rate for long-term deposits in India. However, we also use a 3% rate (savings bank interest rate prevailing in 2013) to arrive at a range rather than a single number.

[6]We declared that all data and information were to be used for academic purposes (PhD thesis of the first author and any academic publication out of it) with due acknowledgment to the funding sources and that no information would be shared for commercial purposes.

[7] The questionnaire is provided in the Appendix.

We estimated the magnitude of the rebound effect by studying how access to efficient lighting and a solar microgrid changed energy-use patterns and the socio-economic impacts of the same.

4.1 The Socio-economic Structure of the Village

Cultivation was the major occupation in the study village. About 70% of the households in the village were engaged in cultivating different varieties of pulses. A few individuals worked as marginal labourers (21%) in various menial jobs like construction, long-distance truck driving, and intermediate short distance non-motorized cart driving (7%). Some households received a secondary source of income from wage earnings during the non-agricultural seasons. It was difficult to determine their exact incomes because householders did not have fixed monthly incomes, salary slips, or registered labour incomes. Our survey data revealed that two households were below the poverty line and the rest were only marginally above it. All the households were in the low-income category. The income from marginal labour was approximately $6.35 per day (₹400).[8] The cultivation workforce was mostly from within the family, and they mainly practised subsistence farming where they produced crops for their consumption. The average monthly expenditure per household was $97.5 (₹6,142.5). The minimum and maximum reported monthly expenditures were $31.75 (₹2,000) and $174.6 (₹11,000), respectively. Among the villagers, 62% were male and 38% female; 54% were adults and 46% were below 18 years of age. Only two adults had a formal education. Those under 18 years, however, attended school at Khareda regularly. All the households had a residential unit with an average carpet area of 871 sq ft. The predominant materials used to construct house walls were mud and unburnt bricks (93% households), whereas the predominant material used to make the roof was asbestos (86% households). About 14% of residential units had tiles on their roofs. Most of the residential units were single-storied buildings with one or two rooms and an open balcony in front of the rooms. Villagers used this balcony as a kitchen and living and dining space. We present some village characteristics vis-à-vis the state in Table 2.

[8] All conversion rates are for the year 2013.

Table 2: Socioeconomic Status of the Study Area

	Study area	State: Rajasthan	Country: India
Principal crop cultivated	Pulses	Barley, wheat, gram, pulses, and oil seeds	Wheat, rice, pulses, and jute
Main source of livelihood	Cultivation and labour	Cultivation	Cultivation
Average monthly family expenditure	\$97.5 (₹6,142.5)	\$50 (₹3,200)	\$18–21 (₹1,175–1,350)
Gender ratio (Female: male)	666:1000	861:1000	940:1000
Literacy rate	Very low (2% approximately)	61.44%	74%
Predominant material of the wall	Mud and unburnt bricks	Stone: packed with mortar	Burnt brick
Predominant material of the roof	Asbestos cement	Stone/slate	Concrete

Source: Census of India (2011); Ministry of Statistics and Programme Implementation (2012)

4.2 Access to Energy Sources

At the time of the survey, households were either using energy sources available in the market or their own sources. They were using kerosene, wood fuel, dung cakes, solar microgrid electricity, and battery power. Each household had one ration card issued against the name of the male head of the family, which gave them access to the public distribution system (PDS). Each household, or each ration card, was allocated four litres of kerosene per month. Kerosene is widely used in cooking (Lam *et al.* 2012), but in the surveyed village, households used wood fuel and dung cakes for cooking and kerosene for agricultural purposes like operating irrigational pump-sets and spraying fertilizers. Kerosene was not used for cooking also because there was a cultural preference for *chulah* (mud-oven) cooked food. For lighting, all the households have been using solar panels and lanterns since 2003–04. While the lanterns only provide a maximum of four hours of illumination service per day, under the new solar microgrid system, a household has access to round-the-clock electricity for illumination and space-cooling (fans or room coolers could be connected). If necessary, and if they could afford to pay, they could also connect other household appliances like televisions, buttermilk machines, grinders, etc.

Table 3: Major Energy Services and their Sources of Energy

Energy service	Lighting (illumination)	Space-cooling	Other energy services
Pre-solar microgrid electricity access	Solar panel with a domestic lantern system (4 hr/day) [90%]	None [0%] (Personal hand fan only)	None [0%]
Post-solar microgrid electricity access	Solar microgrid electricity [77%] (24 hrs/day)		
Change in usage	Consumption increased [77%]	New electric ceiling fans installed [65%]	Buttermilk machines and televisions were purchased and installed in 5% of the surveyed households

Source: Household sample survey
Note: Percentage of households is in parentheses.

The solar microgrid gave households access to both illumination and cooling services. Earlier, households could not have possibly used appliances like fans or coolers/heaters because of affordability issues.

4.3 Solar Microgrids and Electricity Access

The solar microgrid system installed in the study village was of 2 kW capacity. Households paid in advance for the energy service. A 100% advanced payment helped the producer ensure that there was demand for the installed capacity, and people were used to such arrangements because they were familiar with mobile phone recharge services. The households adopted the payment system without any hesitation. The producers engaged a technician to collect the money. Based on the specific needs of households and the amount paid, the power company's controller used the house's consumer identification number to set the individual household meter through a wireless network. A connection used for a minimum of two lights bulbs could be recharged at $0.80 (₹50) and a minimum of two lights and one fan at $2.78 (₹175). On average, in a month, a household spent $0.32 (₹20) on recharges, and the modal value of recharge payment was $0.80 (₹50). This was possible because monthly recharges were not mandatory. A household could recharge again after the amount was exhausted. Thus, there was no specific monthly electricity bill in these households. Households could decide on their service demand level according to what they could afford at that time.

Before getting access to the solar microgrid, most households had just one or two solar lamps from the 2003–04 programme. They had been using these appliances for nine to ten years. A few of them needed replacement appliances (14%). During the survey, we observed that the solar microgrid company had provided all village households with new microgrid connections with two 6 W compact fluorescent lamps (CFL) worth $28.57 (₹1,800) free of cost. If a household used a 6 W CFL for one hour, it cost $0.0024 (₹0.15) under the solar microgrid scheme. Similarly, if they used a 40 W fan for one hour, it cost $0.059 (₹0.37). So, a household paid $0.40 (₹25) per unit (kWh) of solar microgrid electricity.

This amount is nearer the electricity rate in the US ($0.48/unit or ₹30/unit in March 2013) and is much higher than the cost of India's grid-connected electricity ($0.13/unit ₹8/unit in March 2013, on average). It is worth mentioning that the price of grid-connected electricity in India in 2013 included a subsidy of 20–50% at the consumer end. The installation cost of a solar microgrid system is two-and-a-half times higher than setting up a connection to the centralized grid electricity supply system (CEA 2012). In the case of energy-efficient appliances, the capital cost or initial purchase cost is also a significant catalyst for energy consumption. However, energy-efficient technologies have a higher initial cost that acts as a barrier to faster adoption, especially in developing countries (Fowlie *et al.* 2018; GEA 2012; Toman 2003; Bruckner *et al.* 2014). Therefore, the estimation process needs to consider the fixed capital cost and variable costs and calculate the annualized cost for each type of equipment for energy access.

In a supply-constrained scenario, comparing the costs of two competing systems (domestic solar lantern systems and microgrid connectivity systems) generates interesting results. The annualized cost per unit (kWh) of electricity from a community-scale solar microgrid is still much lower than the cost of the electricity generated from the solar home lantern system (Table 4). This is due to the up-front cost of the individual solar panel for the domestic lantern system. So individual households with access to community-scale solar microgrids benefit from economies of scale and get electricity at a cheaper price when compared with the domestic lantern system. In monetary terms, our estimates show that individual households can save approximately $0.21 (₹13) on one unit (kWh) of energy if they switch from individual PV-based systems to microgrid systems. Annually one household can save around $142 (₹8,946) by using the solar microgrid.

Table 4: Energy Sources and Their Corresponding Costs, Services, Appliances in Use, and Average Time of Usage

Energy sources	**Domestic solar panel lighting systems**	**Solar microgrid electricity**				
Time of access (hrs)	4	24				
Annualized cost per kWh energy ($)	0.95* 0.74**	0.64* 0.59**				
Services provided	Lighting only	Lighting	Cooling	Entertainment	Cooking	Other
Appliances in use	Solar lamp	CFL, night bulb	Fan, cooler	Television, radio, DVD player	Buttermilk machine	Mobile charging
Duration of use in a household (hrs/day)	4	4-6 (CFL) 3–5 (night bulb)	2–6 (fan) 2–4 (cooler)	2–4 (television)	1–1.5	2–4

Source: Estimates based on household sample survey data
Note: *Estimated using 8% of the discount rate.
**Estimated using 3% of the discount rate.

Therefore, for the end-users in our case study, it is economic to use community-scale microgrid electricity. This has been shown in other literature as well (Chaurey and Kandpal 2010). Our survey revealed that with 24x7 access to the solar micro-grid, households preferred to keep one light bulb outside their homes illuminated for at least eight hours after sunset for security reasons. When you consider that the domestic solar lamps only provided four hours of illumination, it is easy to see that access to energy from the microgrid and efficient electric appliances doubled the consumption of energy services in the sample households.

Above 90% of respondents agreed that the socio-economic condition of end-users has improved with 24x7 access to electricity from the solar microgrid.[9] The demand for entertainment services via television and radio

[9]Rest of the 10% of the respondent choose not to specify anything.

use have also increased. People are less afraid of insect attacks at night; public places feel more secure; women can cook food even after sundown, which gives them flexibility when it comes to other chores and has allowed them to do more productive work; students have more time to study as they can study at night too. In the village we studied, the basic need was illumination as the village layout was open enough for there to be natural ventilation. Demand for household appliances for food preparation went up when a new appliance—the buttermilk machine—was purchased by some of the households. The uptake rate was as high as 77%, signifying that what was once accomplished using women's physical labour was now being done by modern electric appliances.

Table 5: The Perceived Impact of 24x7 Electricity

Perceived impact of efficient electrification	**Yes (% of responses)**	**No (% of responses)**	**Don't know (% of responses)**
Indoor environment becomes less smoky	100%	0%	0%
Increase in demand for lighting/cooling	100%	0%	0%
Increase in study time for children	100%	0%	0%
More time allocation for daily primary jobs like cultivation	100%	0%	0%
Better livelihood practices with electricity	100%	0%	0%
Others	90% mentioned other benefits such as increased access to entertainment services via television and radio, less fear of insect attacks at night, and flexible cooking times		

Source: Estimates based on household sample survey data

4.4 Avoided Direct Emission

The total demand for energy in the village was 2 kWh per day, as determined by the maximum capacity of the system. If this same amount of energy had been generated by a centralized, thermal electricity grid, 3.56 kg of CO_2 would have been produced per day (1,299 kg of CO_2 per year), assuming an emissions factor of 0.89 tons of CO_2 for every megawatt-hour of electricity (CEA 2012). The solar microgrid system in our case study helped to avoid 3.56 kg of direct CO_2 emissions per day. However, when considering these avoided emissions, one needs to keep in mind the costs involved. From the generation company's perspective, avoiding the 3.56 kg of CO_2 caused an additional 54% generation cost compared to the centralized grid-connected power supply system in India. This was estimated based on CEA data from 2012 about the cost of power projects per megawatt.

4.5 Changes in Electricity Service Demand

A key aim of the survey was to understand the energy service demand patterns of households before and after they got access to the solar microgrid. The annualized per unit cost of electricity from the solar microgrid was found to be 32% lower than in the case of the solar lantern system. The annualized unit cost of electricity services was used to estimate the percentage change in the price of energy services at the household level. Corresponding changes in the demand for illumination services and all-encompassing electricity services have been estimated in Table 6.

Table 6: Estimated Frontier Rebound Effect

Energy services	(At 8% discount rate)	(At 5% discount rate)	Implication of estimated rebound effect
For illumination services	151%	165%	Presence of the frontier effect
For all the available energy services	192%	199%	Presence of the frontier effect

Source: Estimates based on the data from the household survey

The rebound estimates clearly show that the percentage change in the demand for energy services with respect to the price of those services was more than 100%. Thus, a 1% decrease in prices will result in a 1.51–1.65% increase in the demand for illumination services and a 1.92–1.99% increase for all other available energy services. This is because consumers earlier had unmet energy demands because of the constraints of only four hours of access to electricity. After the solar microgrid was set up, they had uninterrupted supply of electricity throughout the day. However, it must be noted that there is an upper limit to the amount of electricity that the community can draw from the microgrid system, i.e., based on its initial capacity on installation. Frontier estimates can be higher than the estimated values when supply is unlimited. The literature suggests that with the introduction of efficient appliances, the energy demand will increase manifold to satisfy unmet demand.

The frontier rebound effect arose in this case study because households increased their direct energy consumption. Their newfound access to affordable electricity allowed them to adopt new appliances (fans, radios, televisions, cell phones, and kitchen appliances) that led to these communities, who had no previous access to modern energy, to demand new energy services that can be considered welfare-enhancing (Saunder, 2013; Jenkins *et al.* 2011). Therefore, the study's estimate is conceptually equivalent to the frontier rebound estimate suggested by other literature (Jenkins *et al.* 2011; Saunders 2013; Saunders and Tsao 2012; Tsao *et al.* 2010; Sorrell 2007, 2009). A rebound case study in rural India (Roy 2000) estimated a partial rebound effect at about 50% for illumination services after introducing only solar lanterns. That was lower than this study's estimated rebound magnitude. For some households, Roy (2000) observed that the rebound effect was about 200% for both lighting and cooking services, which are quite close to the rebound estimates of this study. In another study by Burgess *et al.* (2019), the researchers found high price responsiveness for diesel, off-grid, and microgrid solar in the state of Bihar, India. Such high demand elasticities are striking when compared to those in developed countries where saturated demand levels and high-income levels mean that the demand curve is expected to be almost vertical. Thus, only extensive changes in price can induce changes in demand in those countries.

In our study, we found that 23% (or 5 out of 22) of the households had not taken a solar microgrid electricity connection because they found the costs prohibitive. These households were using the solar lantern system with a battery that let them run at least one light bulb at night; however they found the 24x7 electricity service too expensive. However, it is likely that these households will eventually switch services, either after the lifetime of their current equipment or when their incomes improve. Households that cannot afford the switch can be offered support through new policies that, for example, buy back older solar panels and lighting systems. How such policies can be operationalized, or what other alternative institutional or policy arrangements can be made, are research questions for the future.

5. CONCLUSION

The case study shows that electrification via solar microgrids offers rural households in India social, economic, and environmental benefits. Solar microgrid systems combined with energy-efficient end-use appliances result in a quick reduction in the demand gap. Lessons learned from the case study are relevant at the policy level as well. In contrast to newly emerging research (Lee *et al.*, 2020; Burgess *et al.*, 2019), this study clearly shows that poor rural households in India value round-the-clock access to electricity service. It reduces the drudgery of physical labour and provides flexibility in how time can be productively utilized, especially for women. Therefore, access to electricity, from a class and gender perspective, can be considered essential in terms of a decent standard of living and the Sustainable Development Goals (Hayward and Roy 2019; Rao and Min 2018). The study found that solar microgrids offered many additional benefits to a remote village: increased security in public places at night, access to entertainment services, pest reduction, and more time for students to study. In the village we studied, households consumed very little electricity (around 0.2 kWh per day) compared to an average household in India (12 kWh per day). This can be seen as an indicator of the electricity demand gap, where there is scope for accelerated provision of access to electricity.

The frontier rebound effect of illumination services is estimated to be more than 100%, which implies that a 100% increase in energy efficiency will increase the demand for energy services by more than 100% because of the shift in consumption. This signifies an improvement in end-user utility and thus the well-being of low-income households. This result is consistent with existing literature that postulates that the introduction of energy-efficient supplies will increase demand manifold. In the context of energy-access-equity-driven climate policy, where the goal is to reduce energy poverty and unmet energy demand, the frontier rebound effect can indicate whether the implementation of energy-efficiency policies affect the rate at which unmet demand is reduced.

ACKNOWLEDGEMENT

The authors acknowledge the active cooperation of the CEO of the private microgrid power producer and distributor in India. We are thankful to Mr Suman Dutta from Global Change Programme of Jadavpur University (GCP-JU) for his support in collecting data and Dr Shyamashree Dasgupta for her valuable comments on an earlier version of this article. The authors also acknowledge the financial support from GCP-JU for the field study. Debalina Chakravarty acknowledges the introduction to the private microgrid power producer and distributor in India and is grateful for the short-term fellowship grants from the Development Impact Lab (DIL), University of California, Berkeley, USA, and to the West Bengal State Government Doctoral Fellowship Programme, India, at the Department of Economics, Jadavpur University. Joyashree Roy acknowledges funding under the EDIT-AIT project. EDIT-AIT project at the Asian Institute of

Technology, Thailand received funding from the Energy Demand changes Induced by Technological and Social innovations (EDITS) project, which is part of the initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA) (and funded by Ministry of Economy, Trade, and Industry (METI), Japan). All conclusions and errors are the responsibilities of the authors and reflect their research analysis and do not reflect any other institutions' viewpoint.

REFERENCES

Allan, Grant, Ian Bryden, Peter G McGregor, Tim Stallard, J Kim Swales, Karen Turner, and Robin Wallace. 2008. "Concurrent and Legacy Economic and Environmental Impacts from Establishing a Marine Energy Sector in Scotland." *Energy Policy* 36(7): 2734–2753. https://doi.org/10.1016/j.enpol.2008.02.020

Allan, Grant, Nick Hanley, Peter G McGregor, J Kim Swales, and Karen Turner. 2006. "The Macroeconomic Rebound Effect and the UK Economy." London: The Department of Environment Food and Rural Affairs.

Alliance for Rural Electrification. 2011. *Rural Electrification with Renewable Energy: Technologies, Quality Standards and Business Models*. Brussels, Belgium: The Alliance for Rural Electrification (ARE).

Berkhout, Peter HG, Jos C Muskens, and Jan W Velthuijsen. 2000. "Defining the Rebound Effect." *Energy Policy* 28(6–7): 425-432. https://doi.org/10.1016/s0301-4215(00)00022-7

Binswanger, Mathias. 2001. "Technological Progress and Sustainable Development: What About the Rebound Effect?" *Ecological Economics* 36(1): 119–132. https://doi.org/10.1016/s0921-8009(00)00214-7

Bruckner, T, IA Bashmakov, Y Mulugetta, H Chum, A de la Vega Navarro, J Edmonds, A Faaij, *et al*. 2014. "Energy Systems." In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by O Edenhofer, R Pichs-Madruga, Y Sokona, E Farahani, S Kadner, K Seyboth, A Adler, *et al*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Burgess, Robin, Michael Greenstone, Nicholas Ryan, and Anant Sudarshan. 2019. "Demand for Electricity in a Poor Economy." Unpublished manuscript, University of Chicago.

CEA (Central Electricity Authority). 2012. "Review of Power Sector Report." Ministry of Power, Government of India. Accessed on 24 May 2015. https://cea.nic.in/wp-content/uploads/2020/04/generation_review-2012.pdf

Chakravarty, Debalina. 2016. "Rebound Effect: Empirical Evidence from the Indian Economy." PhD diss., Jadavpur University, Kolkata.

Chakravarty, Debalina, and Joyashree Roy. 2017. "The Global South: New Estimates and Insights from Urban India." In *Rethinking Climate and Energy Policies*, edited by Tilman Santarius, Hans Jakob Walnum, and Carlo Aall, 55–72. Cham: Springer.

Chakravarty, Debalina, Shyamasree Dasgupta, and Joyashree Roy. 2013. "Rebound Effect: How Much to Worry?" *Current Opinion in Environmental Sustainability* 5(2): 216–228. https://doi.org/10.1016/j.cosust.2013.03.001

Chaurey, Akanksha, and Tara Chandra Kandpal. 2010. "Assessment and Evaluation of PV-based Decentralized Rural Electrification: An Overview." *Renewable and Sustainable Energy Reviews* 14(8): 2266–2278. https://doi.org/10.1016/j.rser.2010.04.005

Chen, Changsong, Shanxu Duan, Tong Cai, Bangyin Liu, and Gangwei Hu. 2011. "Smart Energy Management System for Optimal Microgrid Economic Operation." *IET Renewable Power Generation* 5(3): 258–267. https://doi.org/10.1109/ipemc.2009.5157753

Culp, Archie W. 1979. *Principles of Energy Conversion*. Tokyo: McGraw-Hill Kogakusha.

Dieckmann, Ulf. 2013. "Techno-economic Analysis of Microgrid for Universal Electricity Access in Eastern Cape, South Africa." International Institute for Applied Systems Analysis (IIASA). Accessed on 24 May 2015. http://www.iiasa.ac.at/web/scientificUpdate/2013/Longe.html

Druckman, Angela, Mona Chitnis, Steve Sorrell, and Tim Jackson. 2011. "Missing Carbon Reductions? Exploring Rebound and Backfire Effects in UK Households." *Energy Policy* 39(6): 3572–3581. https://doi.org/10.1016/j.enpol.2012.06.045

Filippini, Massimo, and Shonali Pachauri. 2004. "Elasticities of Electricity Demand in Urban Indian Households." *Energy Policy* 32(3): 429–436. https://doi.org/10.1016/s0301-4215(02)00314-2

Fowlie Meredith, Yashraj Khaitan, and Catherine Wolfram. 2018. "Solar Microgrids and Remote Energy Access: How Weak Incentives Can Undermine Smart Technology." Berkely, CA: Energy Institute at Haas.

Freeman, Rachel. 2018. "A Theory on the Future of the Rebound Effect in a Resource-constrained World." *Frontiers in Energy Research* 6: 81. https://doi.org/10.3389/fenrg.2018.00081

Frondel, Manuel, Jörg Peters, and Colin Vance. 2008. "Identifying the Rebound: Evidence from a German Household Panel." *The Energy Journal* 29(4): 145–163. https://doi.org/10.5547/issn0195-6574-ej-vol29-no4-7

Global Energy Assessment (GEA). 2012. *Toward a Sustainable Future*. Cambridge, UK, New York, NY, USA, Laxenburg, Austria: Cambridge University Press and the International Institute for Applied Systems Analysis.

Government of India. 2011. "Census of India 2011." New Delhi: Office of the Registrar General. Accessed on 24 April 2018. http://censusindia.gov.in/

Greening, Lorna A, David L Greene, and Carmen Difiglio. 2000. "Energy Efficiency and Consumption—The Rebound Effect—A Survey." *Energy Policy* 28(6–7): 389–401. https://doi.org/10.1016/s0301-4215(00)00021-5

Hayward, Bronwyn, and Joyashree Roy. 2019. "Sustainable Living: Bridging the North-South Divide in Lifestyles and Consumption Debates." *Annual Review of Environment and Resources* 44(1): 157–175. https://doi.org/10.1146/annurev-environ-101718-033119

Herring, Horace. 1998. "Does Energy Efficiency Save Energy: The Implications of Accepting the Khazzoom-Brookes Postulate." Energy and Environment Research Unit, The Open University. Accessed on 24 May 2015. http://web.mit.edu/2.813/www/readings/HorraceHerring.pdf

Herring, Horace. 2006. "Energy Efficiency—A Critical View." *Energy* 31(1): 10–20. https://doi.org/10.1016/j.energy.2004.04.055

Hirsch, Adam, Yael Parag, and Josep Guerrero. 2018. "Microgrids: A Review of Technologies, Key Drivers, and Outstanding Issues." *Renewable and Sustainable Energy Reviews* 90: 402–411. https://doi.org/10.1016/j.rser.2018.03.040

Jenkins, J, T Nordhaus, and M Shellenberger. 2011. "Energy Emergence: Rebound and Backfire as Emergent Phenomena." *Breakthrough Institute*, February 17. https://thebreakthrough.org/articles/new-report-how-efficiency-can

Johnson, Michael A, and Ranyee A Chiang. 2015. "Quantitative Guidance for Stove Usage and Performance to Achieve Health and Environmental Targets." *Environmental Health Perspectives* 123(8): 820–826. https://doi.org/10.1289/ehp.1408681

Kamel, Rashad M, Aymen Chaouachi, and Ken Nagasaka. 2015. "Wind Power Smoothing Using Fuzzy Logic Pitch Controller and Energy Capacitor System for Improvement Micro-Grid Performance in Islanding Mode." (Retraction of vol 35: 2119, from 2010). *Energy* 85: 688–688. https://doi.org/10.1016/j.energy.2015.05.001

Kaundinya, Deepak Paramashivan, P Balachandra, and NH Ravindranath. 2009. "Grid-connected Versus Stand-alone Energy Systems for Decentralized Power—A Review of Literature." *Renewable and Sustainable Energy Reviews* 13(8): 2041–2050. https://doi.org/10.1016/j.rser.2009.02.002

Khazzoom, J Daniel. 1980. "Economic Implications of Mandated Efficiency in Standards for Household Appliances." *The Energy Journal* 1(4): 21–40. https://doi.org/10.5547/issn0195-6574-ej-vol1-no4-2

Lam, Nicholas L, Kirk R Smith, Alison Gauthier, and Michael N Bates. 2012. "Kerosene: A Review of Household Uses and Their Hazards in Low and Middle-Income Countries." *Journal of Toxicology and Environmental Health, Part B* 15(6): 396–432. https://doi.org/10.1080/10937404.2012.710134

Lee, Kenneth, Edward Miguel, and Catherine Wolfram. 2020. "Does Household Electrification Supercharge Economic Development?" *Journal of Economic Perspectives* 34(1): 122–44. https://doi.org/10.3386/w26528

Lin, Boqiang, and Hongxun Liu. 2015. "A Study on the Energy Rebound Effect of China's Residential Building Energy Efficiency." *Energy and Buildings* 86: 608–618. https://doi.org/10.1016/j.enbuild.2014.10.049

Lin, Boqiang, and Xia Liu. 2013a. "Electricity Tariff Reform and Rebound Effect of Residential Electricity Consumption in China." *Energy* 59: 240–247. https://doi.org/10.1016/j.energy.2013.07.021

Lin, Boqiang, and Xia Liu. 2013b. "Reform of Refined Oil Product Pricing Mechanism and Energy Rebound Effect for Passenger Transportation in China." *Energy Policy* 57: 329–337. https://doi.org/10.1016/j.enpol.2013.02.002

Millward-Hopkins, Joel, Julia K Steinberger, Narasimha D Rao, and Yannick Oswald. 2020. "Providing Decent Living with Minimum Energy: A Global Scenario." *Global Environmental Change* 65: 102168. https://doi.org/10.1016/j.gloenvcha.2020.102168.

Molina, M. G., and P. E. Mercado. 2010. "Stabilization and Control of Tie-Line Power Flow of Microgrid including Wind Generation by Distributed Energy Storage." *International Journal of Hydrogen Energy* 35(11): 5827–5833. https://doi.org/10.1016/j.ijhydene.2010.02.090

MoSPI (Ministry of Statistics and Programme Implementation). 2012. "Household Consumption of Various Goods and Services in India: NSS 66 Round." Government of India. Accessed on 24 April 2018. http://mospi.nic.in/sites/default/files/publication_reports/nss_report_541.pdf

Parikh, Jyoti. 2011. "Hardships and Health Impacts on Women due to Traditional Cooking Fuels: A Case Study of Himachal Pradesh, India." *Energy Policy* 39(12): 7587–7594. https://doi.org/10.1016/j.enpol.2011.05.055

Rao, Narasimha D, and Jihoon Min. 2018. "Decent Living Standards: Material Prerequisites for Human Wellbeing." *Social Indicators Research* 138(1): 225–244. https://doi.org/10.1007/s11205-017-1650-0

Roy, Joyashree, Shyamasree Dasgupta, and Debalina Chakravarty. 2013. "Energy Efficiency: Technology, Behavior, and Development." In *The Handbook of Global Energy Policy,* edited by Andreas Golthau, 282–302. Boston, MA: Wiley Blackwell.

Roy, Joyashree. "The Rebound Effect: Some Empirical Evidence from India." 2000. *Energy Policy* 28(6–7): 433–438. https://doi.org/10.1016/s0301-4215(00)00027-6

Saunders, Harry D. 2005. "A Calculator for Energy Consumption Changes Arising from New Technologies." *The BE Journal of Economic Analysis & Policy* 5(1). http://www.bepress.com/bejap/topics/vol5/iss1/art15

Saunders, Harry D. 2000. "A View from the Macro Side: Rebound, Backfire, and Khazzoom–Brookes." *Energy Policy* 28(6–7): 439–449. https://doi.org/10.1016/s0301-4215(00)00024-0

Saunders, Harry D, and Jeffrey Y Tsao. 2012. "Rebound Effects for Lighting." *Energy Policy* 49: 477–478. https://doi.org/10.1016/j.enpol.2012.06.050

Saunders, Harry. 2013. "Is What We Think of as "Rebound" Really Just Income Effects in Disguise?" *Energy Policy* 57: 308–317. https://doi.org/10.1016/j.enpol.2013.01.056

Sorrell, Steve, and John Dimitropoulos. 2008. "The Rebound Effect: Microeconomic Definitions, Limitations and Extensions." *Ecological Economics* 65(3): 636–649. https://doi.org/10.1016/j.ecolecon.2007.08.013

Sorrell, Steve. 2009. "Jevons' Paradox Revisited: The Evidence for Backfire from Improved Energy Efficiency." *Energy Policy* 37(4): 1456–1469. https://doi.org/10.1016/j.enpol.2008.12.003

Sorrell, Steve. 2007. "The Rebound Effect: An Assessment of the Evidence for Economy-Wide Energy Savings from Improved Energy Efficiency." UK Energy

Research Centre. Accessed on 24 May 2020. https://ukerc.ac.uk/publications/the-rebound-effect-an-assessment-of-the-evidence-for-economy-wide-energy-savings-from-improved-energy-efficiency/
Thirumurthy, N, L Harrington, D Martin, Leena Thomas, Jigmet Takpa, and Reuben Gergan. 2012. "Opportunities and Challenges for Solar Minigrid Development in Rural India." No. NREL/TP-7A20-55562. Golden, CO: National Renewable Energy Laboratory (NREL).
Toman, M. 2003. "'Greening' Economic Development Activities for Greenhouse Gas Mitigation.", Issue Brief, RFF IB 03-02. Washington, DC: Resources for the Future.
Tsao, Jeffrey Y, Harry D Saunders, J Randall Creighton, Michael E Coltrin, and Jerry A Simmons. 2012. "Solid-state Lighting: An Energy–Economics Perspective." *Journal of Physics D: Applied Physics* 43(35): 354001. https://doi.org/10.1088/0022-3727/43/35/354001
United Nations Environment Programme. 2017. "The Emissions Gap Report 2017." Nairobi: UNEP.
Vachirasricirikul, Sitthidet, and Issarachai Ngamroo. 2011. "Robust Controller Design of Heat Pump and Plug-in Hybrid Electric Vehicle for Frequency Control in a Smart Microgrid Based on Specified-Structure Mixed H2/H∞ Control Technique." *Applied Energy* 88(11): 3860–3868. https://doi.org/10.1016/j.apenergy.2011.04.055
Venkataramanan, Giri, and Chris Marnay. 2008. "A Larger Role for Microgrids." *IEEE Power and Energy Magazine* 6(3): 78–82.
Vikström, Peter. 2008. "Energy Efficiency and Energy Demand: A Historical CGE Investigation on the Rebound Effect in the Swedish Economy 1957." *Semantic Scholar*. Accessed 16 July 2021. https://www.semanticscholar.org/paper/Energy-efficiency-and-Energy-Demand%3A-A-Historical Vikstr%C3%B6m/bc1f02c02f799a884a2456bb111142b3faf41363
Wang, Hao, and Jianwei Huang. 2014. "Hybrid Renewable Energy Investment in Microgrid." In *2014 IEEE International Conference on Smart Grid Communications (Smart Grid Comm)*, 602–607. https://ieeexplore.ieee.org/document/7007713
Wei, Taoyuan. 2010. "A General Equilibrium View of Global Rebound Effects." *Energy Economics* 32(3): 661672. https://doi.org/10.1016/j.eneco.2009.09.002
Williams, Nathaniel J, Paulina Jaramillo, Jay Taneja, and Taha Selim Ustun. 2015. "Enabling Private Sector Investment in Microgrid-based Rural Electrification in Developing Countries: A Review." *Renewable and Sustainable Energy Reviews* 52: 1268–1281. https://doi.org/10.1016/j.rser.2015.07.153
World Bank. 2010. "Addressing the Electricity Access Gap." Background Paper for the World Bank Group Energy Sector Strategy. Accessed on 24 May 2015. http://siteresources.worldbank.org/EXTESC/Resources/Addressing_the_Electricity_Access_Gap.pdf
World Bank. 2008. "Designing Sustainable Off-Grid Rural Electrification Projects: Principles and Practices." Operational Guidance for World Bank Group Staff. Accessed on 24 May 2015. https://www.reseau-cicle.org/wp-content/uploads/riaed/pdf/OffgridGuidelines.pdf

World Bank. 2008. "Grid-connect Electricity Supply in India." Accessed on 24 May 2015. http://envfor.nic.in/downloads/public-information/GridconnectElectricittSupplyIndia.pdf

Appendix
Questionnaire for Rural Household Units

Usage pattern of lighting and space cooling in India's rural household sector

---

This questionnaire collects information on ownership patterns and usage of energy-efficient appliances in India as a part of a study on estimating the rebound effect in energy consumption in the Indian economy. The research is being carried out by

----

REQUEST FROM THE RESEARCHERS

It will take you approximately 15 minutes to respond to the questionnaire. Please take some time to answer the questions carefully. This will help us capture a set of crucial information. We would appreciate your responses.

We assure you that your personal information will be kept confidential and your responses will be used purely for academic purposes. We shall be thankful to you for your completing the questionnaire and helping us in our research study.

With regards,

Name of the investigator:
…………………………………………………………………..

Date: ……………………...…. *Time:* …………………. *Signature:*
..............................…

1. Name of the respondent:
   a) Address:
   b) Contact number:

A. Personal Details

1. Age of the respondent:
2. Highest level of education attained by any family member:[10]
3. Are you one of the earning members of the family? Yes/ No
4. How many earning members are there in your family?
5. What is the composition of your family (mention numbers)?

---

[10] (a) < class 10 (b) class 10–12 (c) above 12 but not graduate (d) graduate (e) post-graduate and above

	Adult	Children
Male		
Female		

6. Carpet area of your living space (in sq ft):
7. Is the residential unit owned by you or rented? Yes/ No
8. Family monthly income level:
9. Family monthly expenditure level:
10. Major source of income/major occupation?[11]
11. What are the predominant materials of the roof and walls of your house?
    a) Wall:[12]
    b) Roof:[13]

B. Energy Consumption Details

12. Source of energy:

a) Pre-electricity access scenario:

Energy services	Fuel type used[14] (in the last 3 months)	Amount of fuel used (specify the unit) (per month)	Expenditure on fuel used (in INR) (per month)
Lighting			
Space cooling			

b) Post-electricity access scenario:

[11] (1) Cultivator, (2) main worker (< 6 months), (3) marginal worker, (4) agricultural labourer, (5) household industry worker, (6) other worker.

[12] (1) Grass/thatch/bamboo, (2) wood, (3) mud/unburnt brick, (4) plastic/polythene, (5) burnt brick, (6) stone, (7) GI metal/asbestos sheets, (8) concrete, (9) any other.

[13] (1) Grass/thatch/bamboo, wood, mud, etc, (2) plastic/polythene, (3) tiles (handmade tiles/machine-made tiles) (4) burnt brick, (5) stone, (6) G.I. metal/asbestos sheets, (7) concrete, (8) any other.

[14] (1) Coal, (2) coke, (3) electricity, (4) kerosene, (5) solar, (6) LPG, (7) petrol, (8) diesel, (9) wood fuel, (10) dung cakes, (11) others

Energy services	Fuel type used[15] (in the last 3 months)	Amount of fuel used (specify the unit) (per month)	Expenditure on fuel used (in INR) (per month)
Lighting			
Space cooling			

13. Total electricity consumption pattern:[16]

Months	Units consumed	Expenditure on electricity (in INR)
June		
May		
April		
March		
February		
January		

14. Total electricity consumed in the last 2–3 months:

[15] (1) Coal, (2) coke, (3) electricity, (4) kerosene, (5) solar, (6) LPG, (7) petrol, (8) diesel, (9) wood fuel, (10) dung cakes, (11) others

[16] Investigators are requested to fill the questions of this section himself/herself from the latest electricity bill of the respondent.

15. Consumption pattern of appliances:

Service	Specification	Wattage consumption	Hours in use in summer	Hours in use in winter	First cost/ capital cost	Remark/other details
Post electricity access consumption pattern (in 2012–2013)						
Lighting	Incandescent 100 W					
	Incandescent 60 W					
	Incandescent 40 W					
	Night bulbs 15 W					
	TFL (T5, T8, T12)					
	Tube 2 ft (narrow)					
	Tube 4 ft (narrow)					
	Tube 2 ft (regular)					
	Tube 4 ft (regular)					
	CFL (retrofit/non retrofit) (mention W-5/7/9/11/23)					
	Total					
Space cooling	Ceiling fan (32", 48", 52")					
	AC (0.75, 1, 1.5, 2 ton)					
	Total					
Other (Specify)						

C. Perception about the impact of efficient electrification

16. Do you feel that your environment has become less smoky? Yes/No/Don't know
17. Have you increased your lighting/space-cooling service consumption? Yes/No/Don't know
18. Do you think your kids now have more time for study? Yes/No/Don't know
19. Do you think you can now give more time to your daily primary job like cultivation, etc.? Yes/No/Don't know
20. Do you think now you have a better livelihood with electricity? Yes/No/Don't know
21. Any other impacts (please specify):

End of survey. Thank You!

Promoting reductions in fossil energy demand

Linda Steg, University of Groningen, Department of Psychology

EDITS report, March 2022

Abstract

Many people across the world believe climate change is happening and caused by human behaviour (Capstick et al. 2015; Leiserowitz et al. 2021; Steg, 2018), and are generally motivated to enhance the wellbeing of others and to protect nature and the environment (i.e., they strongly endorse altruistic and biosheric values, respectively; Bouman & Steg, 2019; De Groot et al. 2012; Jakovcevic & Steg 2013; Hanel et al. 2018; Hiratsuka et al. 2018; Sargisson et al. 2020; Steg 2016; Ünal et al. 2019). Such beliefs and values encourage climate action, including reductions in fossil energy demand (from now on referred to as sustainable energy behaviour). Specifically, people are more likely to engage in sustainable energy behaviour when they more strongly believe anthropogenic climate change is happening (Hornsey et al. 2016, Van Valkengoed et al. 2021), and when they more strongly care about others, nature and the environment (see Steg 2016, and Steg & De Groot 2012, for reviews).

Yet, despite this, many people do not consistently engage in sustainable energy behaviours, because they lack the ability to do so (e.g., knowledge, financial resources), or because the context inhibits such sustainable action. This paper reviews which strategies can increase the likelihood that people act upon their climate change beliefs, and altruistic and biospheric values. Moreover, although people generally have strong climate change beliefs, and strongly endorse altruistic and biospheric values, the strength of these beliefs and values differs across individuals. This implies that some groups are likely to be relatively less strongly motivated to engage in sustainable energy behaviour. Therefore, the paper next discusses which strategies can increase sustainable energy behaviour among those who do not strongly care about others, nature and the environment, and climate change.

2022

Building self-sufficiency- A dream or reality? - Modelling the net-zero potential of the global building sector

DIANA ÜRGE-VORSATZ, SOURAN CHATTERJEE, GERGELY MOLNAR, BENEDEK KISS, DANIEL TOPAL

CENTRAL EUROPEAN UNIVERSITY
DBH INNOHUB
BUDAPEST, MARCH, 2022

Table of Content

Executive summary 5

1. Background and introduction: 7

 1.1 Global energy trends in climate neutrality context 7

 1.2 Importance of the building sector 13

 1.3 Objective of the report 15

 1.4 Structure of the report 15

2. Overview of existing modelling trends related to the building sector 16

3. Introduction to the modelling suits (HEB and BISE) 18

 3.1 High-efficiency buildings (HEB) model: 18

  3.1.1 General description: 18

  3.1.2 Methodology: 18

  3.1.3 Implementation 37

 3.2 Building Integrated Solar Energy (BISE) model: 38

  3.2.1 General description 38

  3.2.2 Calculation procedure 38

  3.2.3 Description of modeling inputs 47

  3.2.4 Scenario description 53

4. Results and discussion 53

 4.1 The potential of energy demand reduction 53

  4.1.1 The future dynamics of global floor space 54

  4.1.2 Estimating final annual energy demand 58

  4.1.3 Estimating hourly building energy demand 65

  4.1.4 CO_2 emission potential of the building sector 71

  4.1.5 Sensitivity analysis 74

 4.2 The potential of on-site solar energy production 76

  4.2.1 Estimating building rooftop area 76

  4.2.2 Estimating inter-annual building solar energy supply 78

  4.2.3 Estimating intra-annual building solar energy supply 85

  4.2.4 Verification of the BISE model 87

 4.3 Analyzing the energy balance 89

5. Conclusion and policy recommendations 93

References 95

List of figures:

Figure 1. Energy demand of the building sector across key regions and the World in the four scenarios compared to 2022 levels.......... 5
Figure 2. Projected changes of technical potential for building-integrated total solar energy supply by regions and building types between 2022 and 2060.......... 6
Figure 3. The comparison of hourly specific energy demand for space heating, cooling and hot water production and PV electric energy supply on global level in 2022 (a) and in 2060 (b – Moderate; c – Deep).......... 6
Figure 4. The real and predicted annual change of primary energy consumption globally between 2000 and 2020 (BP, 2021).......... 8
Figure 5. The estimated change of energy demand in 2021 as per fuel type and geographical areas relative to 2019 (IEA, 2020).......... 9
Figure 6. Geographical share of coal consumption between 2000 and 2021 (IEA, 2020).......... 10
Figure 7. The absolute change of the natural gas demand over the last 2 years by different regions and sectors (IEA, 2020).......... 10
Figure 8. The absolute change of renewable electricity generation over the last 2 years by different regions and sectors (IEA, 2020).......... 11
Figure 9. Global CO_2 emission by the energy sector between 1990 and 2021 (IEA, 2020).......... 12
Figure 10. The direct (light blue) and embodied (blue) CO_2 emission by the building sector between 1990 and 2019. After 2019, an estimation compatible with the IEA's Sustainable Development Scenario (SGS) is shown (IEA, 2020).......... 13
Figure 11. Global final energy demand by end uses between 2010 and 2018 (UNEP, 2019).......... 14
Figure 12. Global coverage of HEB model.......... 18
Figure 13. The main workflow of HEB. Input data and Parameters can be modified by the user (green). Main outputs are the floor areas of different building vintage types as well as energy consumption and CO2 emission of the stock (blue).......... 21
Figure 14. Yearly floor area dynamics of the HEB model.......... 25
Figure 15. Occupancy schedule of residential buildings.......... 30
Figure 16. Occupancy schedule of office buildings.......... 30
Figure 17. Example of water mains temperature calculation based on Burch and Christensen (2007). 32
Figure 18. Hot water usage schedule of residential buildings.......... 32
Figure 19. Hot water usage schedule of office buildings.......... 33
Figure 20. Spatial distribution of the developed climate classification used in the HEB and BISE models.......... 37
Figure 21. Subset of HSL data overlaid by building cadaster (Granada, Spain).......... 49
Figure 22. Hourly weights [in UTC] of computed for the wind speed on January 1st 2022 in the grid point (55, 55).......... 50
Figure 23. Global distribution of derived global radiation input on July 1st 2022.......... 51
Figure 24. Electric and thermal efficiencies of the reviewed PV/T collector products.......... 51
Figure 25. Reviewed values of the PV/T collector's temperature coefficient.......... 52
Figure 26. The relative change of the utilization factor in the BISE's scenario. The relative utilization expresses the PV or PV/T coverage on building rooftops relative to the suitable rooftop area.......... 53
Figure 27. Change in total floor area with respect to urban / rural context as well as building category 55
Figure 28. Distribution of World total floor area by building vintages across the modelling period.......... 55
Figure 29. Distribution of total floor area in China by building vintages across the modelling period. 56
Figure 30. Distribution of total floor area in the USA by building vintages across the modelling period. 56

Figure 31. Distribution of total floor area in the Pacific OECD by building vintages across the modelling period. 56
Figure 32. Distribution of total floor area in India by building vintages across the modelling period. 57
Figure 33. Distribution of total floor area in the EU by building vintages across the modelling period. 57
Figure 34. Total final energy consumption in the World and in key regions (in PWh). 59
Figure 35. Total final energy consumption in the World by building category and classification (in PWh) 60
Figure 36. Final energy consumption for space heating, cooling and hot water production in given regions and climate zones predicted by the DEEP scenario (in PWh). 60
Figure 37. Share of regions within the total heating and cooling energy consumption of the World. 61
Figure 38. Final energy for space heating and cooling in focus countries and the World according to the scenarios. 62
Figure 39. Share of regions within the total heating and cooling energy consumption of the World. 62
Figure 40. Final energy consumption for hot water production in focus countries according to the three scenarios. 64
Figure 41. Share of building category within the World final energy consumption for hot water production in PWh. 65
Figure 42. Hourly total energy demand on global level in 2060, by end-uses and scenarios. 67
Figure 43. Hourly final energy demand for space heating on global level in 2060, by different scenarios. 67
Figure 44. Hourly final energy demand for space cooling on global level in 2060, by different scenarios. 68
Figure 45. Hourly final energy demand for hot water production on global level in 2060, by different scenarios. 68
Figure 46. Hourly final energy consumption for space heating, cooling and hot water production in given regions and climate zones predicted by the DEEP scenario 2060 (in PWh). 69
Figure 47. Comparison of the mean daily variation of the end-use energy demand in India in January of 2022 and 2060 according to the Deep efficiency scenario. 69
Figure 48. Comparison of the mean daily variation of the end-use energy demand in India in July of 2022 and 2060 according to the Deep efficiency scenario. 70
Figure 49. Comparison of the mean daily variation of the end-use energy demand in the USA in January of 2022 and 2060 according to the Deep efficiency scenario. 70
Figure 50. Comparison of the mean daily variation of the end-use energy demand in the USA in July of 2022 and 2060 according to the Deep efficiency scenario. 71
Figure 51. CO_2 footprint of building energy demand over the modelling period, by end-uses and scenarios. 72
Figure 52. CO_2 footprint of space heating and cooling energy demand over the modelling period in the key regions, by end-uses and scenarios. 73
Figure 53. Sensitivity of the total final energy consumption to the level of accelerated retrofit rate. 74
Figure 54. Sensitivity of the total final energy demand to the delay in introduction of advanced requirements for new and retrofitted buildings. 75
Figure 55. Sensitivity of the total final energy demand to the energy intensity value of advanced new and advanced retrofitted buildings. 76
Figure 56. Total roof area in each region in 2022. 77
Figure 57. Projected changes of solar system area by regions and building type between 2022 and 2060. 78
Figure 58. Projected changes of technical potential for solar electric energy supplied by PV/T modules in different regions between 2022 and 2060. 79

Figure 59. Projected changes of technical potential for solar electric energy supply by PV/T modules in different regions and building types between 2022 and 2060. 80
Figure 60. Projected changes of technical potential for solar thermal energy supply by PV/T modules in different regions between 2022 and 2060. 81
Figure 61. Projected changes of technical potential for solar thermal energy supply in different regions and building types between 2022 and 2060. 82
Figure 62. Projected changes of technical potential for building-integrated total solar energy supply by regions and building types between 2022 and 2060. 83
Figure 63. Baseline and scenario-based projection of technical rooftop PV energy supply between 2022 and 2060. The dashed lines indicate the level of global building electricity consumption in 2019. 84
Figure 64. Estimated mean monthly variability of PV/T technical potential by solar electric (blue curves) and thermal (red curves) energy production [in kWh/m^2] in different regions over the analyzed period. 86
Figure 65. Estimated mean hourly variability of PV/T technical potential by solar electric (blue curves) and thermal (red curves) energy production [in kWh/m^2] in different regions during the summer solstice (2060). 87
Figure 66. Estimated mean hourly variability of PV/T technical potential by solar electric (blue curves) and thermal (red curves) energy production [in kWh/m^2] in different regions during the winter solstice (2060). 87
Figure 67. The comparison of hourly specific energy demand for space heating, cooling and hot water production and PV electric energy supply on global level in 2022 (a) and in 2060 (b – Moderate; c – Deep). 90
Figure 68. The comparison of hourly specific energy demand for space heating, cooling and hot water production and PV in different key regions by 2060 (Deep Efficiency scenario). 91
Figure 69. The comparison of hourly specific energy demand for space heating, cooling and hot water production and PV in different key regions and climate zones by 2060 (Deep Efficiency scenario). 92

List of tables:

Table 1. Parameters of the four scenarios. 19
Table 2. Building classification scheme of HEB. 20
Table 3. Developed climate classification system used in the HEB and BISE models. 36
Table 4. Auxiliary table for the Perez's transposition model to determine coefficients based on ε values (Perez et al., 1990). 43
Table 5. Roof to floor ratios due to regions and building types used in the model (Petrichenko, 2014). 47
Table 6. Estimated values of U_F coefficients separated by flat and pitched roofs. 48
Table 7. Technical specification of hypothesized PV and PV/T modules used during the modeling activity. 52
Table 8. Results for total final energy use in the key regions and the World. 61
Table 9. Results for final energy use for heating and cooling in the key regions and the World. 63
Table 10. Results for final energy use of hot water production in the key regions and the World. 65
Table 11. Total building-related CO_2 emission in the key regions and the World. 72
Table 12. Space heating and cooling CO_2 emission in the key regions and the World. 73
Table 13. Comparison of the technical potential of rooftop PV electricity simulated by the baseline and deep utilization cases. 85

Executive summary

According to the Intergovernmental Panel on Climate Change's (IPCC) Working Group I in the Sixth Assessment Report (AR6) (Masson-Delmotte, V. et al., 2021), the elevated level of human-induced greenhouse gas (GHG) emission leads to an increase in the global surface temperature, which is "0.8°C to 1.3°C, with a best estimate of 1.08°C". This report also highlighted that the rate of the global warming is "unprecedented in at least the last 2000 years". In order to mitigate the adverse effects of climate change, it is necessary to substantially reduce the GHG emissions both globally and locally. Thus, the building sector would play a key role as the building sector emits 40% of the global CO_2 and contributes to about 33% of the global energy demand presently (Urge-Vorsatz et al., 2020). Hence, understanding the global energy demand of the building sector by assessing the future floor area growth and their respective energy demand is crucial in the context of the 1.5-degree target.

This report makes a first attempt to provide a set of 'what if' scenarios to assess the potential of achieving building net-zero or self-sufficiency status globally under different policy packages. This report explores the future energy demand and onsite energy supply potential for eleven key regions across the globe to analyze the potential achieving net-zero building sector through ambitious sustainable building policies. This study analyses both the energy demand and energy generation potentials of net-zero or advance energy efficiency buildings for 11 key regions across the world with the help of four different scenarios. The initial findings of the study show that with state-of-the-art high-efficiency buildings implemented worldwide, it is possible to achieve self-sufficiency in the future. However, this pathway towards high-efficiency or net-zero is ambitious in its assumptions and requires strong policy support. The findings of the study show that with state-of-the-art high-efficiency buildings implemented worldwide, it is possible to achieve self-sufficiency in the future. However, this pathway towards high-efficiency or net-zero is ambitious in its assumptions and requires strong policy support. Furthermore, the findings also show that climate neutrality or self-sufficiency in buildings can only be achieved if service energy demand of the building end uses is substantially reduced. Irrespective of the regions and climate zones, this argument holds valid.

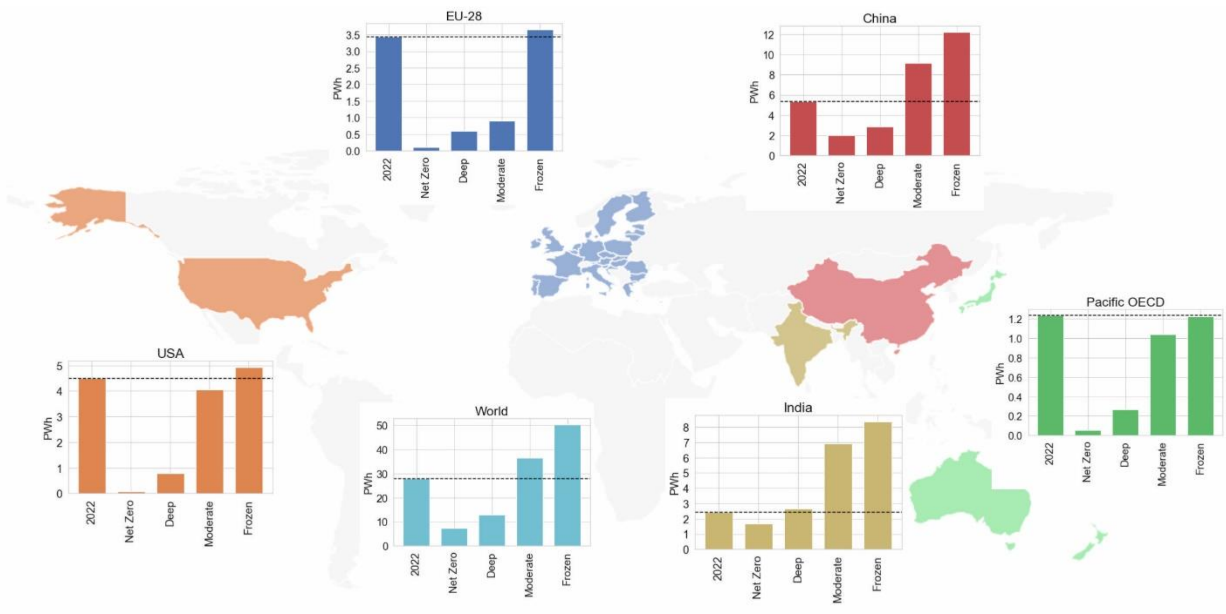


Figure 1. Energy demand of the building sector across key regions and the World in the four scenarios compared to 2022 levels.

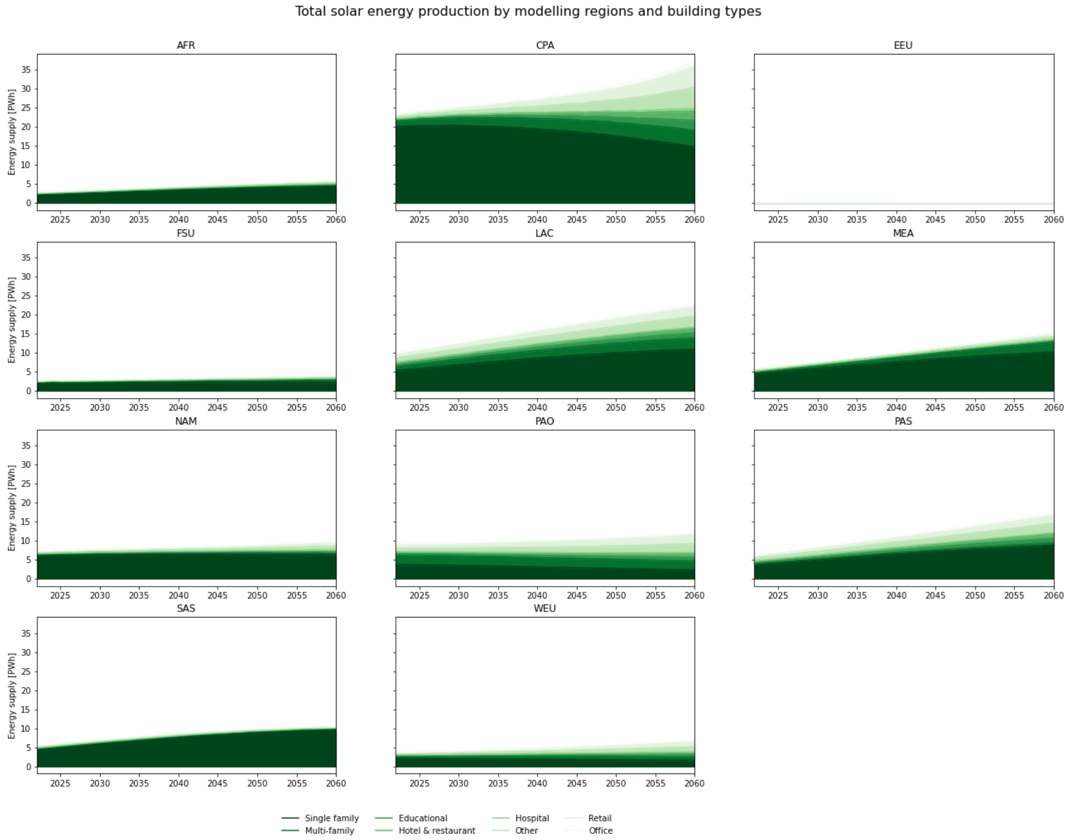


Figure 2. Projected changes of technical potential for building-integrated total solar energy supply by regions and building types between 2022 and 2060.

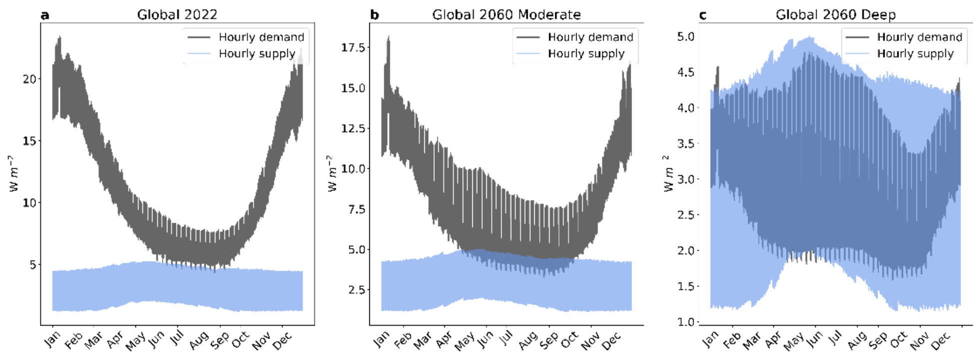


Figure 3. The comparison of hourly specific energy demand for space heating, cooling and hot water production and PV electric energy supply on global level in 2022 (a) and in 2060 (b – Moderate; c – Deep).

1. Background and introduction:

1.1 Global energy trends in climate neutrality context

Climate change is one of the greatest challenges in the history of the humanity (Palmer and Stevens, 2019). According to the Intergovernmental Panel on Climate Change's (IPCC) Working Group I in the Sixth Assessment Report (AR6) (Masson-Delmotte, V. et al., 2021), the elevated level of human-induced greenhouse gas (GHG) emission leads to an increase in the global surface temperature, which is "0.8°C to 1.3°C, with a best estimate of 1.08°C". This report also highlighted that the rate of the global warming is "unprecedented in at least the last 2000 years". Depending on the future GHG emission trends, the escalation of the temperature rise could vary on a very broad range. As the AR6 predicted, based on multiple lines of evidence, the warming will most likely be between 1°C and 5.7°C by 2100 relative to the reference period 1850–1900. It also seems very possible that the negative consequences of global warming and other climate change related events (e.g., sea level rise, increase in temperature and precipitation extremes, etc.) will influence each part of the World in various extent.

In order to mitigate the adverse effects of climate change, it is necessary to substantially reduce the GHG emissions both globally and locally. That is why, under the United Nations Framework Convention on Climate Change, 193 state parties have ratified the Paris Agreement in which, among others, the objective for "holding the increase in the global average temperature well below 2°C above pre-industrial level and pursuing effort to limit the temperature increase to 1.5°C above pre-industrial levels" as well as "foster climate resilience and low greenhouse gas emissions development" (Delbeke et al., 2019). Since the policies of the Paris Agreement have failed to be implemented in the expected pace during the last years (Climate Action Tracker, 2021), the acceleration of decarbonization measures has become very urgent in maintaining the desired climate-resilient pathway. Coming to this realization, governments have announced even more ambitious efforts to meet the climate goals in the 26th Conference of the Parties (COP26) in 2021. Within framework of the "Glasgow Climate Pact", wide spectra of commitments were made with regard to stopping deforestation, phasing out coal, curtailing methane emission, halting oil and gas production, increasing the use of clean energy sources, achieving net-zero economy and enhancing funding to support the transition in developing countries (Allan et al., 2021). The assessment of the Climate Action Tracker shows that the pledges of the COP26 could result in a shrinking gap in the CO_2 emission level between the current and Paris Agreement compatible pathways by 2030. On the other hand, it was also emphasized that much more drastic initiatives are needed to be close to a sustainable track in the forthcoming decades (Climate Action Tracker, 2021)

Since 1982, except for two years (2009 and 2020), the primary energy consumption has shown a year-to-year increase globally, starting from a basis of 276.59 EJ to a level of 581.51 EJ (BP, 2021) (Figure 4). It can be interpreted as that the consumption doubled over the course of the last nearly 40 years. Having same tendencies for the final energy consumption, it peaked at 418 EJ on global scale in 2019, shared chiefly among oil (40.4%), electricity (19.7%) and natural gas sources (16.4%) (IEA, 2021a).

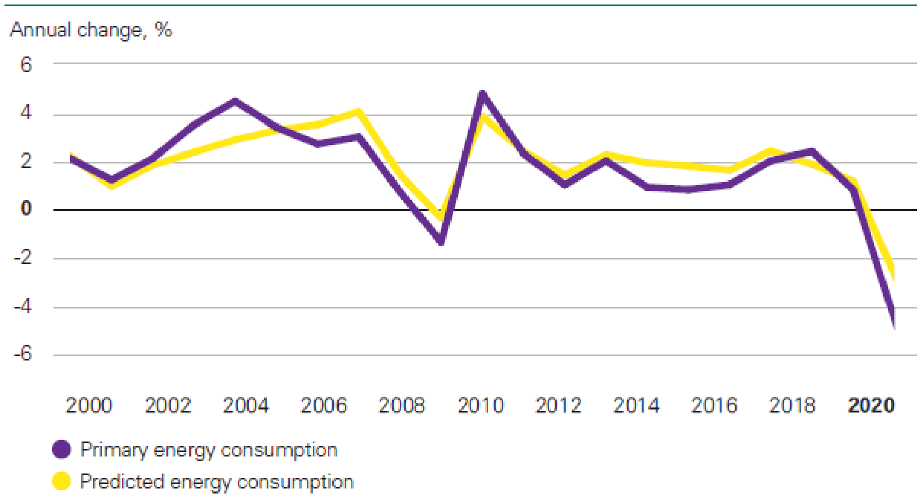


Figure 4. The real and predicted annual change of primary energy consumption globally between 2000 and 2020 (BP, 2021).

The COVID pandemic crisis has made a major impact on the global energy demand in 2020, underlined by the 4% decline in primary energy consumption relative to the 2019 level. In parallel, the CO_2 emission fell by 5.8% (equivalent to 2 Gt CO_2) as a consequence of strict lockdown regulations (IEA, 2020). Nonetheless, the related impact has hit the leading economies in different degree. Besides the general decelerating trend in the USA, EU and India in terms of GDP, energy consumption and GHG emission, China has maintained a growth of 2.3, 2,1 and 0.6% for these indicators, respectively (IEA, 2020). The IEA report (IEA, 2020), however, estimates an economic bounce-back by 2021, which can be explained directly by the effective vaccination, financial supports and more flexible health regulations. The estimated growth of 6% in the GDP in 2021 relative to 2020 (and 2.5% relative to 2019) could push the energy demand and CO_2 emission to an increasing track.

Indeed, the primary energy demand will be 4.6% (0.5%) higher globally in 2021 than in 2020 (2019) (IEA, 2020). However, different waves of coronavirus variants are causing significant uncertainties over the country-level demand trends, it is forecast that major economies have the capacity to partially or fully recover from the crisis (Figure 5). In the USA, the EU, Russia and Japan, the recover seems to be slower (still lower level than in 2019) due partly to the more conservative approach for lockdown and partly to the size of the economy related developing countries. For South Asia, Africa and India, as an example, a rise of around 2% is projected by 2021 relative to the pre-COVID era (IEA, 2020). China, as the most COVID-resilient country among the large economies, is anticipated to continue the growing in the primary energy demand to peak at around 154 EJ in 2021 (BP, 2021).

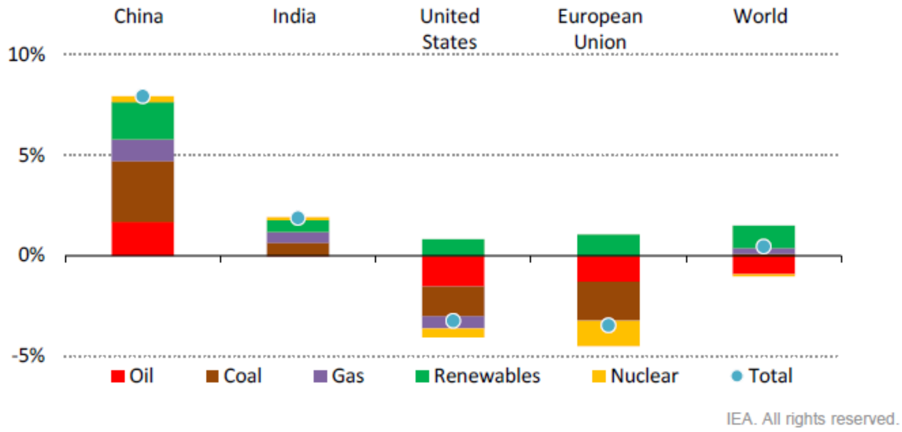


Figure 5. The estimated change of energy demand in 2021 as per fuel type and geographical areas relative to 2019 (IEA, 2020).

As a result of the lockdown regulations, the mobility demand for road transportation and aviation inclined drastically and kept the fuel prices on a historically low level. The oil, as the largest contributor to the fuel mix for primary energy demand, has been impacted mostly by the immobility of people and thus its production shrank by 6.6 million barrel/day in April, 2020 (BP, 2021). Since the mobility demand could recover only in a sluggish pace over the next years (especially kerosene and jet fuel demand for aviation), the demand for oil and its distillates are expected to increase slower as other fuels. In 2021, the oil demand is projected to be around 6% above the 2020 level (94.1 mb/d) (IEA, 2020).

As a consequence of the modernization of power generation in advanced economies and policies to curb coal production, the coal demand has been characterized by stagnation globally since 2015 (Figure 6). In developing countries, especially in China, the demand rises by about 2% per annum between 2009 and 2019. In 2019, the global consumption was 157.64 EJ, and this level was pushed down by the pandemic with 4.2% to 151.42 EJ (BP, 2021). The coal demand in the USA and the EU is estimated to partly recover from the shock in 2021, still indicating lower niveau as in 2019. Additionally, this recover is impacted also by the high carbon prices that inhibit the preference of coal in power supplying (IEA, 2020). In the Asian major markets, the coal demand was projected to bounce back sharply, with definite increases of 4% and 6% in China and India (IEA, 2020). Nevertheless, the ambitious climate efforts to decarbonize the economy during the 21st century and the promotion of alternative energy sources (e.g., renewables) may induce slow shrink in coal utilization, which has already been observable in the OECD countries.

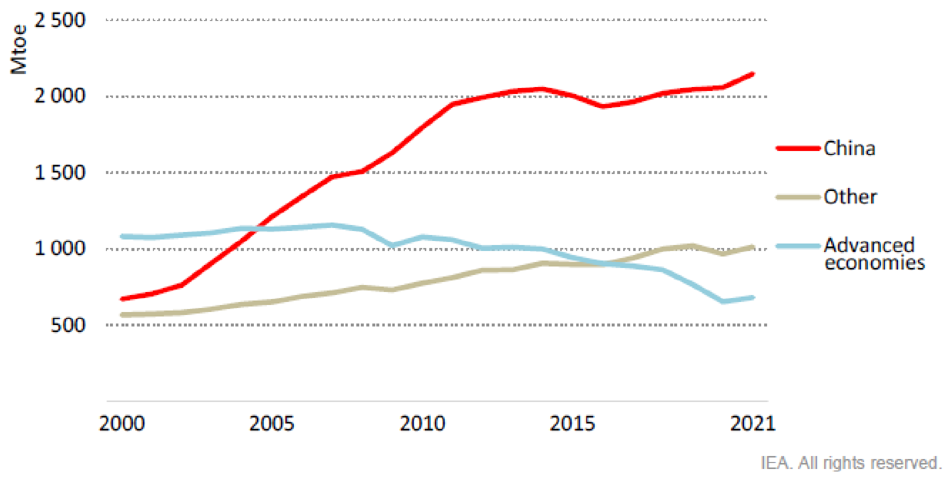


Figure 6. Geographical share of coal consumption between 2000 and 2021 (IEA, 2020).

Between 2009 and 2019, the global consumption of the natural gas followed a growth rate 2.9%/year (OECD countries: 2.1%, non-OECD countries: 3.6%) to reach the overall maximum at 140.54 EJ (BP, 2021). After the significant negative anomaly in 2020, the gas demand starts to rise again in 2021, with 1.3% relative to the year before the health crisis. As the demand boom is sending the carbon prices skyrocketing in the EU and the USA, the emerging fuel competition is favored for the gas consumption in contrast with coal and it promotes faster rebound of natural gas, primarily in these markets (IEA, 2020). Figure 7 suggests increasing demand also in the Middle East and Asia. In Asia this process is triggered by both the extending economies and the increased heating demand for buildings due to long cold periods. Indeed, beside the industry, the building sector is estimated to force most remarkably the rise of natural gas demand in 2021. As the Net Zero report of the International Energy Agency underlines, the current global trends in natural gas consumption must be reversed and the demand should be lowered by 5% per annum to be compatible with climate neutrality purposes (IEA, 2021b). Promoting hydrogen-based fuels, electrification with renewables, bioenergy could help to reduce gas consumption and the corresponding emission footprint.

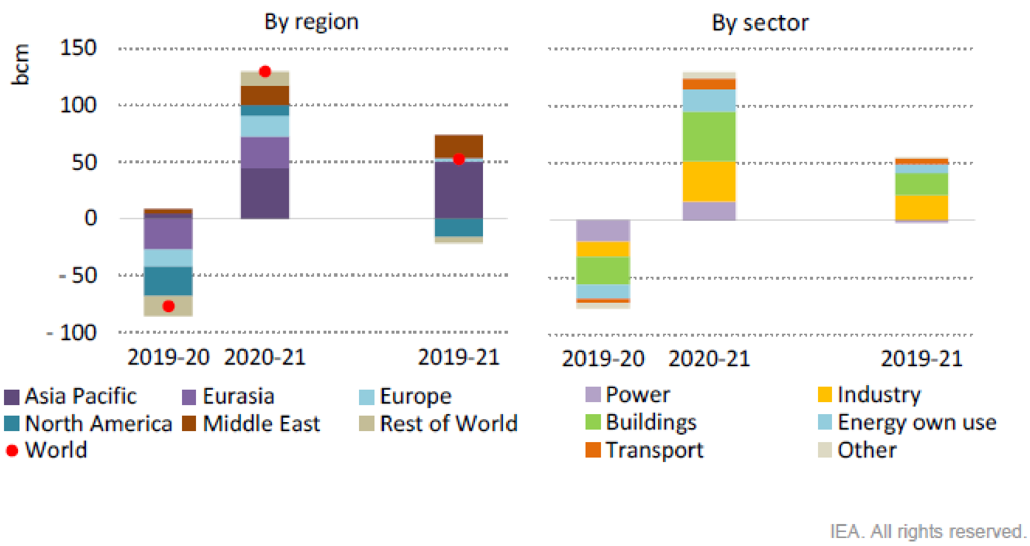


Figure 7. The absolute change of the natural gas demand over the last 2 years by different regions and sectors (IEA, 2020).

Substantially elevating the primary and final energy supply by renewables is decisive to get on a climate-resilient track over the next decades. Renewable energy production has shown continuous development over the years since the 1970s, and this evolution was also proven to be resistant against pandemic crisis in 2020. Quantitatively, the power generation, for example, by renewables rose on a year-on-year basis by 15.3% from 2009 to 2019, and it persisted around 12% in 2020 (equivalent to 3.15 PWh; BP, 2021). As estimated by the IEA (2020b) report, the green electricity generation could continue its tendency at a growth rate of 8% in 2021. In 2019, the share of renewables in the power sector was 23% (IEA, 2021a), fueled by wind (1.42 PWh) and solar energy (0.7 PWh) with around 67% contribution to the total generation.

As of today, Pacific Asia has the largest slice from renewable energy related electricity production among the key regions with 42%. This lead is attributed to China where the share is about in the same extent as in the second region (China: 27.4%, EU: 29.3%) (BP, 2021). About 30% of the PV and wind electricity generation was concentrated to China in 2020 (Figure 8). Additional leading countries in the use of renewables include the USA (17.5% share), Germany (7.4% share) and India (4.8% share). During the last decade, the power generation by solar PV has made substantial progress in all regions and so became increasingly dominant in the share. If these tendencies will be persistent, the shares for wind and PV in electricity generation could be the same by 2050 (IEA, 2021b).

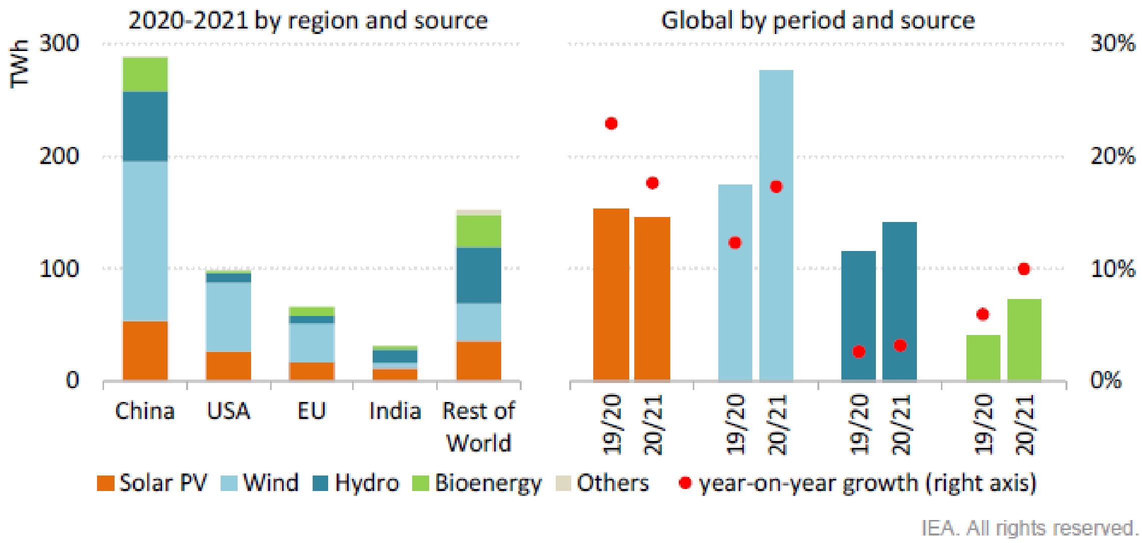


Figure 8. The absolute change of renewable electricity generation over the last 2 years by different regions and sectors (IEA, 2020).

Over the next decades, all significant energy sectors must rely on renewables remarkably. According to the estimation of the IEA (IEA, 2021b), however, minor demand for fossil fuels will still inevitable in some sectors (in less-developed economies preferably) until 2050. For the industrial heating, the sustainable future can be achieved by reducing the consumption of fossil fuels to 10% (71%) by 2050 (2030) and by simultaneously increase the share of renewables (e.g., biogas) and low-carbon sources (e.g., hydrogen). For road transportation, the ratio of carbon-intense and low- (and zero-) carbon fuels should be 10%-90% (45%-55%) by 2050 (2030) (IEA, 2021b). In this process, the global spread of hydrogen-based and electric vehicles is substantially desired. Additionally to industry heat, for this reason, the transport sector is anticipated to decrease its carbon footprint by applying hydrogen or hydrogen-based fuels. The building sector must rely on different solar technologies (e.g., PV, Thermal or PV/T systems) to produce on-site clean electric and/or thermal energy on rooftops. Solar systems solely should occupy 240 million rooftops of residential buildings to push the demand for fossil fuels below 10% globally by 2050 (IEA, 2021b). Moreover, technologies for storing heat and electricity produced at buildings and heat pump investments should be subsidized to obtain net-zero energy level for the building sector (Urge-Vorsatz et al., 2020). The climate-neutral future does not seem realistic without fully decarbonized electricity sector, as it is projected by the IEA (IEA, 2021b) report. To do so, the share of hydrocarbons in electricity generation must shrink to 25% level by 2030. Precisely, the power generation from wind and solar energy sources should be eightfold by 2050 relative to the current niveau. In lower fraction, however, the electricity production should also rely on hydropower (12% share), bioenergy (5%), concentrating solar power (2%) and geothermal energy (1%) (IEA, 2021b).

The global CO_2 emission reached 34 Gt CO_2 in 2019, which was the highest level in the history (IEA, 2021b). As it was pointed out previously, the pandemic-related lockdowns resulted in slight fall in the emission, although similar decreases (e.g., in 2009) have very short lifetime, as it can be observed in Figure 9. Nevertheless, the trend for GHG emission must be reversed to evolve a decarbonized economy, and the global CO_2 emission should be reduced to 21 Gt CO_2 (≈ 40% reduction) by 2030. Seeing little further, all developed countries should be net-zero emitters by 2045, with a 0.5 tons per capita CO_2 emission by the early 2040s, as the IEA analysis (IEA, 2021b) suggests. It is also added that the electricity sector should lead the decarbonization process. For this purpose, by eliminating the coal-based electricity generation entirely, the carbon footprint of the power sector should be reduced with 60% (100%) by 2030 (2040) (IEA, 2021b).

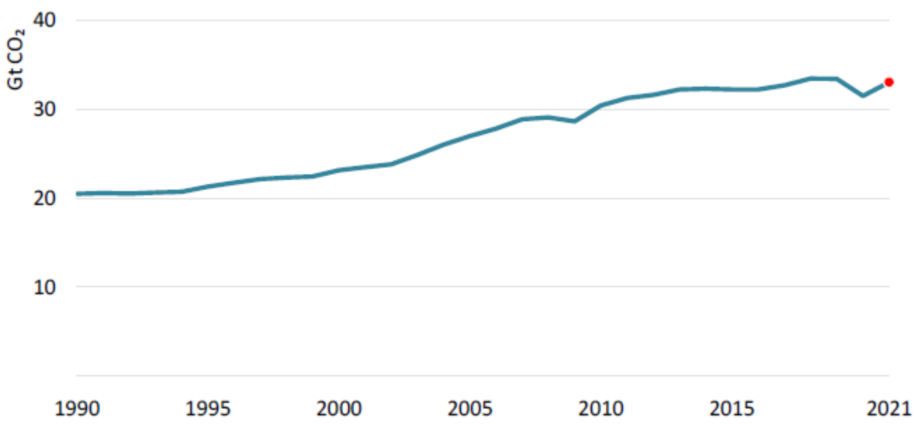


Figure 9. Global CO_2 emission by the energy sector between 1990 and 2021 (IEA, 2020).

For the building and transportation/industry sector, the CO_2 emission must be cut with 40% and 20% by 2030 (IEA, 2021b). The lower initial pace of decarbonization in these sectors is related to that such interventions as retrofitting of energy inefficient buildings or scaling up technologies of low-emission fuels requires more time and more capital injection as compared to the power sector. This is especially true in the case of aviation and heavy industry for which the level of decarbonization is strongly dependent on the evolution of such developing technologies as capturing and storing carbon sources from air or biofuels. Predominantly for the building and transportation sector, the behavioral and lifestyle changes of end-uses could play a pivotal role in mitigating CO_2 emission (Capstick et al., 2014). As the IEA report (IEA, 2021b) estimates, around 15% reduction associated with this factor would be adequate to support, along with other solutions, the net-zero emission pathway for these sectors.

1.2 Importance of the building sector

The building sector emits 40% of the global CO_2 and contributes to about 33% of the global energy demand nowadays. Precisely, the building-related final energy use was 128 EJ globally in 2019 and showed a growth rate of 8% since 2010 (IEA, 2020) (Figure 10). In parallel, the global CO_2 emission of buildings increased over 3Gt, indicating about 5% raise in the last decade (IEA, 2020). Especially in the developing economies, the building stock is predicted to grow substantially until 2050, therefore the floor area will likely to be 75% higher as compared to the current values (IEA, 2021b). This level is reached by extrapolating the current annual floor area growth rate 2.5%. As a result, an increasing energy demand is anticipated over the following decades, which could especially be significant for electric devices and air conditioners (Santamouris and Vasilakopoulou, 2021). Since the current fall in the energy intensity (around 0.5-1% per year; IEA, 2020) is not enough to compensate the annual elevation of floor area, the previous factor must be improved by driving buildings to a much more energy-efficient way. To do this, it could be indispensable to retrofit buildings, applying innovative building designs and heat pumps as well as promoting the electrification of heating/cooling systems of buildings, aiming 50% (66%) share of electricity in the fuel mix by 2030 (2050) (IEA, 2021b).

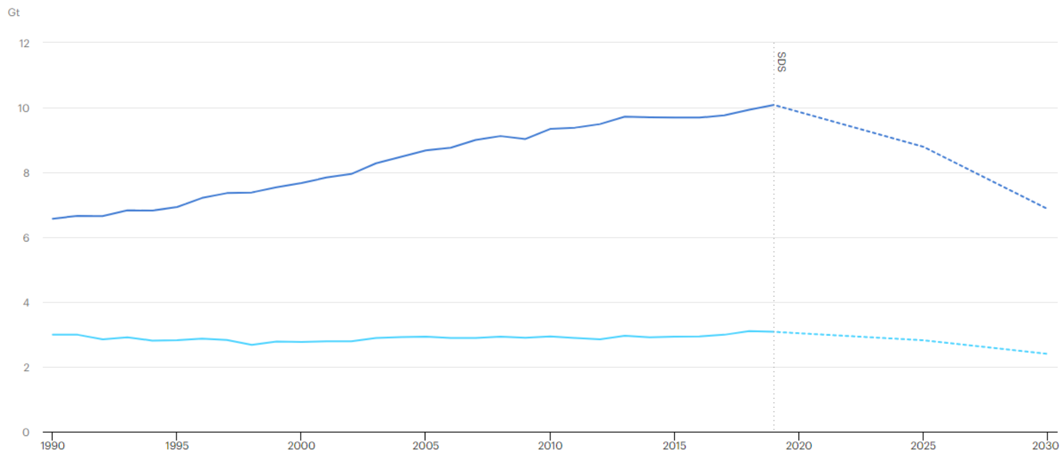


Figure 10. The direct (light blue) and embodied (blue) CO_2 emission by the building sector between 1990 and 2019. After 2019, an estimation compatible with the IEA's Sustainable Development Scenario (SGS) is shown (IEA, 2020).

As modeling studies and other estimations demonstrate (e.g., Boermans et al., 2012; IEA, 2021b), the renovation rate must be 2.5-3% compared to the current 1% to have a realistic chance of delivering the energy efficiency of the building stock to the desired level. Besides, the behavioral and lifestyle changes are also key steps in increasing energy efficiency of buildings (Capstick et al., 2014). These processes should support a decline in the CO_2 emission to the 120 Mt level (95% reduction) until 2050. This is equivalent with a shrink in the fossil fuel demand to 30% and 2% by 2030 and 2050 (IEA, 2021b).

To the electrification of the energy end use activities, renewables can contribute in a high degree, with different utilization potential in space and time. The corresponding need is the highest for such end uses as space heating, cooking and hot water production, although the dynamically increasing demand for space cooling and appliances highlights the importance of complex and flexible solutions (Figure 11).

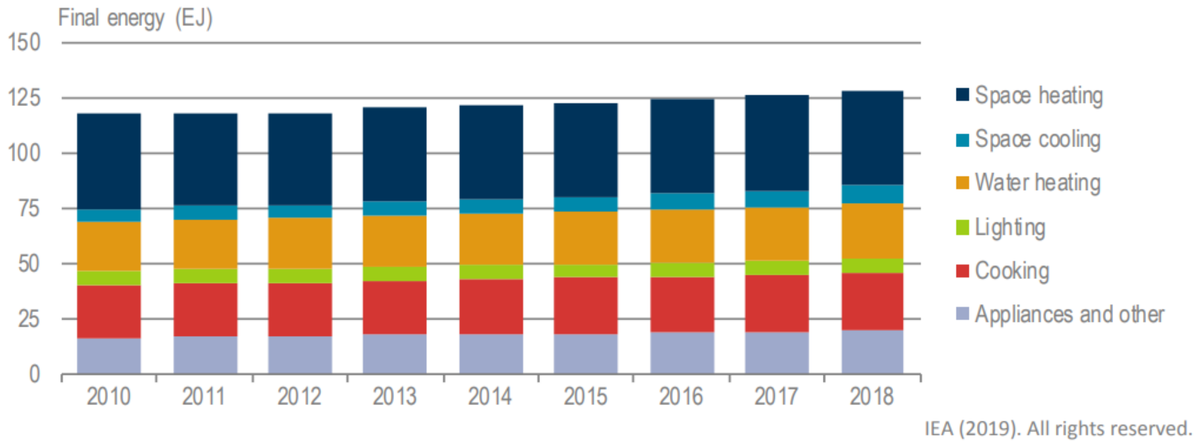


Figure 11. Global final energy demand by end uses between 2010 and 2018 (UNEP, 2019).

Among the potential technologies, solar systems seem to be particularly relevant, as both thermal and electric energy are efficiently producible with the combination of PV panels, thermal collector and hybrid systems. According to Diwania et al. (2020), the building rooftops are still greatly unutilized by solar systems recently. Therefore, there is an immerse rooftop potential of solar energy remained unexplored and can push the transition between fossil and clean energy sources at buildings. For a climate-neutral future, the PV generation must be raised to 7.5 PWh by 2050 globally, as the net-zero scenario of the IEA study (IEA, 2021b) indicates. It is also predicted in this investigation that satisfying the increased demand for electricity at building-level, the number of PV panel systems installed on rooftops should be as high as 240 million (compared to the current value 25 million) by 2050 globally.

Presumably, buildings must also rely on low-carbon fuels (e.g., hydrogen-based fuels and biogas) in the future to supply the demand for space heating and cooking, which may have two explanations. First, in very dense urban centers, the use of auxiliary heat pumps and energy storage is not easily resolvable, thus in these areas the district heating is considered to be the optimal solution (IEA, 2021b). Secondly, installing solar or wind systems is not profitable for either lack of adequate meteorological conditions or lack of financial support (high initial costs and long payback period; Shukla et al., 2017). For such regions, bio fuels could be a reasonable choice to supply energy for space heating and cooking. Bioenergy is expected to have 10% and 20% contribution to the space heating by 2030 and 2050 (IEA, 2021b). Still, electric heat pumps will likely to be the norm in supplying energy for space heating/cooling , along with 6-7 times larger monthly installation numbers as compared to the level of 1.5 million in 2020 (IEA, 2021b).

In summary, the building sector is anticipated to transform significantly over the forthcoming decades. On the one hand, it is related to expansion of building stock in the emerging markets, proportionally to the growth of GDP and population. On the other hand, the rise in the global building energy demand must be forced to offset by reducing substantially the carbon footprints of buildings and by increasing the share of low-carbon and green energy sources. As an outcome of the transformation from carbon-intense to clean energy, more than the 85% of the global building stock should be net-zero by 2050 (IEA, 2021b). It seems obvious that the decarbonization process is expected to rely on cutting edge ("smart") technologies, although there is a need to provide financial and education support for building occupants to be able to change their behavior and lifestyle in terms of energy consumption. Also, renewable energy sources must be key pillars in the transformation of the fuel mix, although no general recipe is seemed in the technological and fuel choice. It will presumably depend on the level of the governmental incentives, awareness of the users and the accessibility of fuels and technologies. In addition to expanding the installed capacity of renewable energy producers, the deep renovation has a great importance in a sustainable building sector. However, on the design of retrofitting and renewable installations, the effect of climate change should also be taken into consideration, which could significantly impact the specific energy demand (both for heating and cooling) of the building sector (van Ruijven et al., 2019) and the behavior of building occupants.

1.3 Objective of the report

The aim of this report is to provide a set of 'what if' scenarios to assess the potential of emission reductions of the building sector globally under different policy packages. Furthermore, this report explores the future energy demand and onsite energy supply potential for twelve key regions across the globe to analyze the potential achieving net-zero building sector through ambitious sustainable building policies. To achieve this aim, this study has following four key objectives:

1. Calculate annual and hourly energy demand profiles for 11 regions across the world. The annual and hourly profile will be calculated up to 2060 under four different policy scenarios, to provide a what-if insight.
2. The hourly and yearly energy demand profile will be calculated for different climate zones in each of the 11 regions based on historical data (NASA MERRA-2 database) and a GIS-based unsupervised classification tool. The classification of the climate zones will be done based on four parameters, heating degree days, cooling degree days, relative humidity, and the average temperature of the warmest month. The climate classification is particularly important to assess the net-zero potential of the building sector as both the energy demand and onsite solar energy supply vary as per different climate zones.
3. To understand the energy-sufficiency potential of the building sector, the hourly demand profiles and hourly integrated solar energy production profiles will be compared for each of the climate zones in each of the 11 regions till 2060.
4. Lastly, based on the demand and supply profiles, the annual CO_2 emission of the building sector will be calculated for each of the regions across the globe till 2060 under different policy scenarios.

With the help of two bottom-up energy demand and supply models, this study analyses building sector-related energy demand and onsite renewable energy production to explore the potential of the building sector in tackling climate change.

1.4 Structure of the report

This report is organized into five sections. The first section introduces the motivation behind this study by introducing the importance of tackling climate change mitigation measures and the role of the building sector to contribute in the science of climate change mitigation measures. Section one further discusses the key trends of energy demand and supply globally. Section two reviews the different energy modelling trends by analyzing the potential of energy demand reduction and onsite supply generation of the building sector. Then in section three, two building sector models namely high-efficiency building (HEB) model and Building Integrated Solar Energy (BISE) model are introduced and discussed along with their methodologies. Section four presents the energy demand and onsite energy supply data respectively for 11 regions across the world. Furthermore, this section also discusses the potential of net-zero building by analyzing the demand and onsite solar energy supply potential of the building sector globally. Lastly, section five concludes the study by discussing the policy relevance of the results from two building models.

2. Overview of existing modelling trends related to the building sector

As already discussed, decarbonizing the building sector is a key pillar to build a climate-resilient future. The literature shows a great agreement in that the realization of this ambitious but necessary goal is influenced by the deepness of financial support, scale and availability of new (renewable and low-carbon) technologies and renovation rate of buildings (Capros et al., 2019; Wolf et al., 2021). The state-of-the-art building energy models, therefore, must be capable of accounting for these factors and being able to incorporate different scenarios to analyze the effects of different policies on the expected trends in building energy demand and GHG emission.

The modeling approach used by these models depends on the scope, time frame and spatial coverage of the analysis. Nonetheless, the building energy models mostly follow two approaches, namely the bottom-up and the top-down approach. These approaches are very different in their consideration on technology. While in the bottom-up models, the technological characteristics of the building sector are incorporated in a very high detail, the top-down models describe these properties through disaggregating higher level statistics of technological and socio-economic databases. By subdividing the energy models by methods, there could also be simulation (and agent-based simulation), optimization, general and partial equilibrium models (Ringkjøb et al., 2018).

Projecting floor area is a key initial step in the building energy models, which is usually based on the robust statistical relationship between floor area and certain socio-economic variables (e.g., population count and GDP). In the models, the buildings stock is often split into residential and tertiary segments and later the floor area is predicted accordingly. In the EDGE model, for instance, the estimated residential floor area is the function of floor space demand per capita, income per capita, population density and ratio of commercial to residential area (Levesque et al., 2018). By employing geospatial data for population, the spatiotemporal dynamics of floor area can be derived in high granularity. Another method for projecting floor area could be the agent-based building stock modeling in which the composition of the stock (i.e., the share of retrofitted and advanced building vintages) relies strongly on the decisions of building agents. As Nägeli et al. (2020) points out, the decision is mostly made by considering its economic viability through energy prices, resource availability and labor costs. A potential uncertainties may rise in this method in estimating interactions between agents (e.g., co-operability), differentiating between building owner types (Preisler et al., 2017). Because of the complexity of the agent-based approach, it is applicable primarily to district or urban-level studies.

The building energy modelers have already realized the significance of simulating renovation as a key driver in turning the building stock energetically much more efficient. Focusing now on the EU-level modeling studies (e.g., Boermans et al., 2012; Ó Broin et al., 2013; Roscini et al., 2020), they concluded that optimal renovation rate should be 2-3% annually by 2050 to be able to retrofit the entire European stock, and to reduce the energy inefficiency to the sufficient level. The findings are in line with the recommendation of 2.5% suggested in the IEA report (IEA, 2021b). It is also added in Roscini et al. (2020) that to decarbonize the building sector in the EU, all buildings must meet the net-zero energy level after the renovation in which the renewables could play a pivotal role.

Recent modeling works have a tendency to put more focus on the possibilities of reaching climate-neutrality on both regional and global. Matthes et al. (2017) presented modeling evidence on that promoting deep renovation, scaling up renewables, electrifying space heating and maximizing energy level at net-zero could lead to major improvements in specific energy demand and CO_2 emission in the EU. They simulated that without major demand for oil and natural gas and by increasing, for example, the share of hydrogen and biogas (to 7% by 2050), biomass (to 26% by 2050) and solar thermal (to 11% by 2050), the climate-neutrality could be realistic in the EU). Knobloch et al. (2021) predicts that phasing out fossil fuels solely for space heating of residential buildings would require a total cost of 176 billion €2005 at EU level. They also quantify the effect of policies for supporting subsidizes and emerging clean technologies on residential energy demand and CO_2 emission and found these interventions effective in terms of demand (98% decrease by 2050) and emission (69% decrease by 2050) reduction. On the other hand, there are few investigations that shed more light on the potential threat in achieving a climate-neutral pathway for the building sector. As Kranzl et al. (2019) points out by comparing seven long-term scenarios of different modeling results, the CO_2 emission will likely exceed the desired level in many EU member states, which may possibly be connection with the low renovation rate, delay in the removal of carbon-based boilers for space heating and sluggish decarbonization of the building-related power and heating production.

On global level, most model experiments aim to give perspective on the building final and useful energy demand as well as fuel mix and GHG emission for a given time frame (typically until 2050) and by disaggregating the outputs by energy carriers, end-uses and regions. Levesque et al. (2018), for instance, used the EGDE model to estimate the global building energy consumption by 2100. By interpreting the Shared Socio-Economic Pathways (SSP) scenarios, they show that the building-related final energy demand could rise to 120-378 EJ/year by 2100 globally, with decreasing demand for space heating and cooking. In terms of fuels, the electricity was modeled to increasingly dominate the mix, which means, as the authors highlight, that clean transformation of the electricity production would be an essential step in mitigating the CO_2 emission. Mastrucci et al. (2021) also applied SSP-based scenarios to analyze the dynamics of building stock, energy demand and CO_2 emission for space heating and cooling. During the modeling activity, carried out with the MASSAGEix-Buildings bottom-up model, the scenarios contained different assumptions for demographics, income, housing, techno-economics and behavior. The simulation results for the heating fuels indicate large drop in the coal, biomass and oil shares and shift towards the intense use of electricity. They estimated that space heating could increasingly rely on heat pumps in hotter climate, while preferring district heating in cold areas. In case of energy efficiency of space heating, the lowest values were projected for new and renovated buildings of the northern hemispheric urban areas. For space cooling, similar spatial characteristics were found. Further, the authors add that the energy intensity for space cooling is largest in high-income households, since they have much easier access to AC relative to low-income households. As a result of the decreasing final energy demand for space heating (more in Europe and USA; less in China and India) and increasing final energy demand for space cooling (more in India and South America; less in Europe), the CO_2 emission was modeled to reduce between 55.7% (SSP1 scenario) and 30% (SSP3 scenario) in the northern hemisphere by 2050, while in the southern hemisphere no reduction included in the simulations. The outlined tendencies for CO_2 emission were explained with the energy efficiency improvements and electrification for space heating and broader utilization of AC by Mastrucci et al. (2021). Similar to these studies, most building energy model experiments do not incorporate the effects of climate change during their long-term projections, and employ typical meteorological year data for representing the atmospheric parameters. As Li et al. (2017) emphasizes, such simplification could raise the uncertainties of the results in these models. Nevertheless, some modeling studies (e.g., Ciancio et al., 2020; van Ruijven et al., 2019) identified this shortcoming and confirmed the importance of the changing climatic drivers on the demand for both space heating and cooling.

3. Introduction to the modelling suits (HEB and BISE)

3.1 High-efficiency buildings (HEB) model:

3.1.1 General description:

HEB model was originally developed in 2012 to calculate energy demand and CO_2 emissions of the residential and tertiary building sector until 2050 under three different scenarios (Urge-Vorsatz, 2012). Since then, the model has been developed and updated several times. With the latest update, the model calculates the energy demand in the four scenarios until 2060 based on the most recent data for macroeconomic indicators and technological development. This model is novel in its methodology as compared to earlier global energy analyses and reflects the emerging new paradigm – the performance-oriented approach to buildings energy analysis. As opposed to component-oriented methods, a systemic perspective is taken: the performance of whole systems (e.g. whole buildings) is studied and these performance values are used as inputs in the scenarios. This model calculates with the overall energy performance levels of buildings regardless of the measures applied to achieve it. Moreover, this model also captures the diversity of solutions required in each region by having region-specific assumptions about advanced and sub-optimal technology mixes. The elaborated model is in the framework of the bottom-up approach, as it includes rather detailed technological information for one sector of the economy, however, it also benefits from certain macroeconomic (GDP) and sociodemographic data (population, urbanization rate, floor area per capita, etc.). The key output of the HEB model consists of floor area projection for different types of residential and tertiary buildings in different regions and Member States, the total energy consumption of residential and tertiary buildings, energy consumption for heating and cooling, energy consumption for hot water energy, total CO_2 emission, CO_2 emission for heating and cooling, and CO_2 emission for hot water energy. The end use demand and its corresponding emission are produced until 2060 at a yearly resolution for 11 key regions with 28 member states and 3 key countries (India, China, and USA) which cover the World (Figure 12).

Figure 12. Global coverage of HEB model.

3.1.2. Methodology:

This model is novel in its methodology as compared to earlier global energy analyses and reflects the emerging new paradigm – the performance-oriented approach to buildings energy analysis. The elaborated model is in the framework of the bottom-up approach, as it includes rather detailed technological information for one sector of the economy, however, it also benefits from certain macroeconomic and sociodemographic data which include population, urbanization rate, floor area per capita. HEB model uses four different scenarios to understand energy use dynamics and to explore the potential of the building sector to mitigate climate change through the various opportunities. The four scenarios are:

1. Deep Efficiency Scenario: Deep Efficiency scenario demonstrates the potential of state-of-the-art construction and retrofit technologies that can substantially reduce the energy consumption of the building sector and hence CO_2 emissions reduction as well, while also providing full thermal comfort in buildings. In this scenario, exemplary building practices are implemented worldwide for both new and renovated buildings.
2. Moderate Efficiency Scenario: Moderate scenario incorporates present policy initiatives particularly the implementation of the Energy Building Performance Directive (EPBD) in the EU and building codes for new buildings in other regions.
3. Frozen Efficiency Scenario: This scenario assumes that the energy performance of new and retrofit buildings do not improve as compared to the baseline and retrofit buildings consume around 10% less than standard existing buildings for space heating and cooling, while most new buildings have a lower level of energy performance than in Moderate scenario due to lower compliance with Building Codes.
4. Nearly Net Zero Scenario: The last scenario models the potential of deploying "Nearly Net Zero Energy Buildings" (buildings that can produce as much energy locally through the utilization of renewables as they consume on an annual balance) around the World. It differs from the other three scenarios to the extent that it not only calculates the energy consumption but already incorporates the local energy supply to arrive at the final energy demand. In other aspects, it uses the same parameters as the Deep Efficiency scenario.

The aim of the scenario analysis is to capture the importance of different policy acts on building energy efficiency measures and show how much the final energy consumption of the building sector can be reduced across the World. Table 1 summarizes the actual parameters of the four scenarios.

Table 1. Parameters of the four scenarios.

Parameter	**Deep Efficiency Scenario**	**Moderate Efficiency Scenario**	**Frozen Efficiency Scenario**	**Net Zero Scenario**
Initial retrofit rate	1.4%	1.4%	1.4%	1.4%
Accelerated retrofit rate	3% in developed countries and 1.5-1.6% in developing countries after 2027	3% in developed countries and 1.5-1.6% in developing countries after 2027	No accelerated retrofit rate is assumed	3% in developed countries and 1.5-1.6% in developing countries after 2027
Energy Efficiency measures of new buildings	New buildings are built to regional standards	New buildings are built to regional standards	New buildings do not improve as compared to the existing stock	New buildings are built to regional standards
Energy efficiency measures of renovated buildings	Renovations reduce the energy demand approximately by 30%	Renovations reduce the energy demand approximately by 30%	Renovations reduce the energy demand approximately by 10%	Renovations reduce the energy demand approximately by 30%

Share of advanced buildings within new and retrofitted stock	All new and retrofitted buildings have very low energy demand after 2030 in EU, NAM, and PAO, and after 2037 in other parts of the World.	Advanced buildings are only introduced in Western Europe, after 2035 all new buildings and after 2045 all retrofitted buildings have very low energy design.	Advanced buildings are only introduced in Western Europe after (1% of the new and retrofitted building stock)	All new and retrofitted buildings have net zero energy demand after 2030 in EU, NAM, and PAO, and after 2037 in other parts of the World.

HEB model conducts scenario analysis for the entire building sector where building sector is distinguished by their location namely rural, urban, and slum, building type, namely single-family, multifamily, commercial, and public buildings with subcategories, and building vintages, namely existing, new, advanced new, retrofit, advanced retrofit. These detailed classifications of buildings are conducted for 11 regions extended with country-specific results for the EU-27 countries as well as China, India, and the USA. Furthermore, within each region different climate zones are considered to capture the difference in building energy use and renewable energy generation caused by climate variations. The climate zones are calculated based on four key climatic factors namely heating degree days (HDD), cooling degree days (CDD), relative humidity of the warmest month (RH), the average temperature of the warmest month (T). These parameters are processed by using the GIS5 tool - spatial analysis – and performed with ArcGIS software. The detailed classification categories are summarized in Table 2.

Table 2. Building classification scheme of HEB.

Classification scope	**Categories**	**subscript notation**
Regions	11 key geographical regions + 30 focus countries	*r*
Climate zones	17 different climate zones	*c*
Urbanization	Urban / Rural areas	*u*
Building category	Residential / Commercial and Public / Slums	*b*
Building type	Single-family houses (SF) / Multi-family houses (MF) (residential sector) Educational / Hotel & Restaurant / Hospital / Retail / Office / Other (commercial & public sector)	*t*
Building vintage	Existing / new / advanced new / retrofit / advanced retrofit	*v*

The purpose of the detailed classifications of building categories and scenario assessments is to explore the consequences of certain policy directions/decisions to inform policymaking.

The key input data used in HEB are the region-specific forecasts for GDP, population, rate of urbanization, and the rate of population living in urban slums. The time-resolution of the model is yearly, so that socio-economic input data can be easily obtained from various credible sources such as databases of the World Bank, UNDP, Eurostat, and OECD. Apart from these socio-economic parameters, there are many other parameters and in case of the absence of data, assumptions are used in the HEB model to calculate final energy demand. Figure 13 below shows the main workflow of the HEB model:

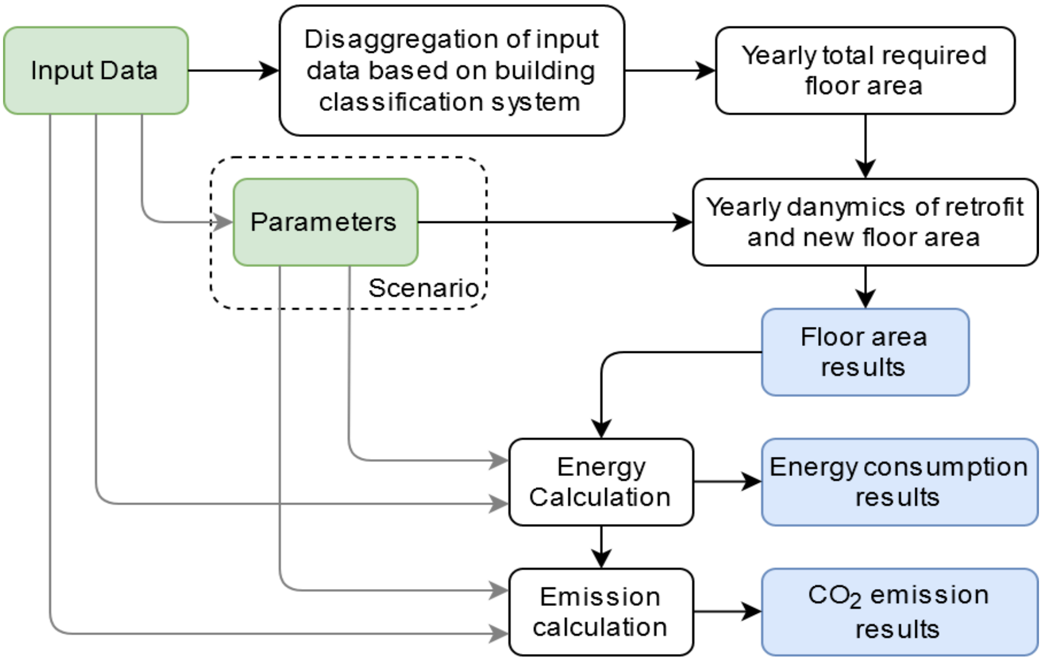


Figure 13. The main workflow of HEB. Input data and Parameters can be modified by the user (green). Main outputs are the floor areas of different building vintage types as well as energy consumption and CO2 emission of the stock (blue).

The HEB model considers several calculation steps from using input data to obtaining the final output. Each of these calculation steps is discussed in the below sections.

3.1.2.1 Disaggregation

At the first step of the calculation, after obtaining all the socio-economic input data, the input is disaggregated into the detailed building classification scheme (Figure 14), and the total required floor area is determined to satisfy the year-specific population and GDP needs (the year is denoted with *Y* in subscript). The core concept of calculating the floor area is different for residential and for commercial buildings:

- For residential buildings, the total occupied floor area correlates with the population, and thus, population forecasts are used to determine the floor area of buildings in each region.
- For commercial and public buildings, the floor area correlates more with GDP, therefore GDP forecasts are used as a proxy to determine the total floor space area of commercial and public buildings.

The region-specific population data – as the input of the calculation – is further disaggregated into urban and rural population based on urbanization rate and into the different climate zones based on GIS data:

$$P_{r,c,u,Y} = P_{r,Y} \times U_{r,Y} \times Sc_{r,c} \quad \text{if } u = urban$$

Equation 1

$$P_{r,c,u,Y} = P_{r,Y} \times \left(1 - U_{r,Y}\right) \times Sc_{r,c} \quad \text{if } r = rural$$

Equation 2

$P_{r,c,u,Y}$ *[capita]* is the total urban/rural population of region *r and* climate zone *c* in year *Y*,

$P_{r,Y}$ *[capita]* is the total population of region *r* in year *Y*,

$U_{r,Y}$ *[-]* is the urbanization rate of region *r* in year *Y*,

$Sc_{r,c}$ *[%]* is the share of population within region *r* living in climate zone *c*.

The urban population is then further disaggregated into the population living in slums (in regions where a significant number of people do not have access to standard living conditions) and the population living in conventional residential buildings. The latter group is split into population living in single-family and multi-family houses based on region-specific fixed values:

$$P_{r,c,u,b,Y} = P_{r,c,u,Y} \times Ss_{r,Y} \quad \text{if } u = urban \text{ and b} = slum$$

Equation 3

$$P_{r,c,u,b,Y} = P_{r,c,u,Y} \times \left(1 - Ss_{r,Y}\right) \quad \text{if } u = urban \text{ and b} = residential$$

Equation 4

$$P_{r,c,u,b,t,Y} = P_{r,c,u,b,Y} \times Ssf_r \quad \text{if } u = urban\text{, b} = residential \text{ and t} = SF$$

Equation 5

$$P_{r,c,u,b,t,Y} = P_{r,c,u,Y} \times (1 - Ssf_r) \qquad \text{if } u = urban\text{, b} = residential \text{ and t} = MF$$

Equation 6

$P_{r,c,u,b,Y}$ *[capita]* is the total urban/rural population of region r, climate zone *c*, building category *b* in year *Y*,

$P_{r,c,u,Y}$ *[capita]* is the total urban/rural population of region *r and* climate zone *c* in year *Y*,

$P_{r,c,u,b,t,Y}$ *[capita]* is the total urban/rural population of region *r*, climate zone *c*, building category *b* and building type *t* in year *Y*,

$Ss_{r,Y}$ *[%]* is the share of urban population living in slums in region *r* and year *Y*,

Ssf_r *[%]* is the share of urban population living in single-family houses in region *r*.

The population living in rural areas is assumed to live in single-family houses.

The disaggregation of GDP follows the same pattern, except that share of GDP that can be associated with rural commercial and public buildings is fixed within the modelling period:

$$GDP_{r,c,u,Y} = GDP_{r,Y} \times \left(1 - U_{r,Y}\right) \quad \text{if } u = urban$$

Equation 7

$$GDP_{r,c,u,Y} = GDP_{r,Y} \times U_{r,Y} \times Sc_{r,c} \quad \text{if } u = rural$$

Equation 8

$GDP_{r,c,u,Y}$	*[USD]*	is the total GDP that can be associated with urban/rural commercial and public buildings in region *r and* climate zone *c* in year *Y*,
$GDP_{r,Y}$	*[USD]*	is the total GDP of region *r* in year *Y*,
$U_{r,Y}$	*[-]*	is the urbanization rate of region *r* in year *Y*,
$Sc_{r,c}$	*[%]*	is the share of climate zone *c* within region *r*.

Also, the share of different commercial building types is determined using fixed ratios based on literature data.

$$GDP_{r,c,u,t,Y} = GDP_{r,c,u,Y} \times Scp_t$$

Equation 9

$GDP_{r,c,u,t,Y}$	*[USD]*	is the total GDP that can be associated with urban/rural commercial and public buildings of type *t* in region *r and* climate zone *c* in year *Y*,
$GDP_{r,c,u,Y}$	*[USD]*	is the total GDP that can be associated with urban/rural commercial and public buildings in region *r and* climate zone *c* in year *Y*,
Scp_t	*[%]*	is the share of commercial and public buildings type *t* in the commercial and public building stock.

3.1.2.1 Determining the total floor area

Floor area calculation for the residential building and non-residential building uses different equations. Calculating the floor area of the residential buildings can be noted with the following equation using specific floor area values (the floor area that is occupied by one person):

$$TFA_{r,c,u,b,t,Y} = P_{r,c,u,b,t,Y} \times SFAc_{r,u,b,t,Y} \quad \text{if } b = residential/slum$$

Equation 10

$TFA_{r,c,u,b,t,Y}$	*[m²]*	is the total urban/rural floor area of building category *b* and building type *t* in region *r and* climate zone *c* in year *Y*,
$P_{r,c,u,b,t,Y}$	*[capita]*	is the total urban/rural population of region *r*, climate zone *c*, building category *b* and building type *t* in year *Y*,
$SFAc_{r,u,b,t,Y}$	*[m²/capita]*	is the specific floor area of building category *b* and buildings type *t* in region *r and* in year *Y*.

Similarly, the floor area of commercial and public buildings is calculated using specific floor area values (floor area that is required to produce one unit of GDP):

$$TFA_{r,c,u,b,t,Y} = GDP_{r,c,u,t,Y} \times SFAg_{r,b,Y} \quad \text{if } b = C\&P$$

Equation 11

$TFA_{r,c,u,b,t,Y}$	*[m²]*	is the total urban/rural floor area of commercial and public buildings of building type *t* in region *r and* climate zone *c* in year *Y*,
$GDP_{r,c,u,t,Y}$	*[USD]*	*i*s the total GDP that can be associated with urban/rural commercial and public buildings of type *t* in region *r and* climate zone *c* in year *Y*,
$SFAg_{r,b,Y}$	*[m²/USD]*	is the specific floor area of commercial and public buildings in region *r and* in year *Y*.

Specific floor area values are determined using statistical data for each region. In order to take socio-economic development into account, the floor area per capita and the floor area per GDP are modelled as yearly changing values, reaching the average of the OECD countries until the end of the modelling period in developing regions.

3.1.2.3 Yearly dynamics of floor area changes

The yearly dynamics of this floor area models the transition of the existing building stock into the future state determined by the scenarios. This includes the retrofit or demolition of existing buildings as well as the introduction of new buildings to the stock. In some cases, floor area is left abandoned which might be a result of population decrease (e.g. in developed regions) or the increased rate of urbanization due to which buildings located in the rural area are abandoned after a certain time-period. This aspect is important to capture, since abandoned buildings do not contribute to the energy consumption and the emissions of the building stock. This yearly dynamic of the building vintage types is presented below.

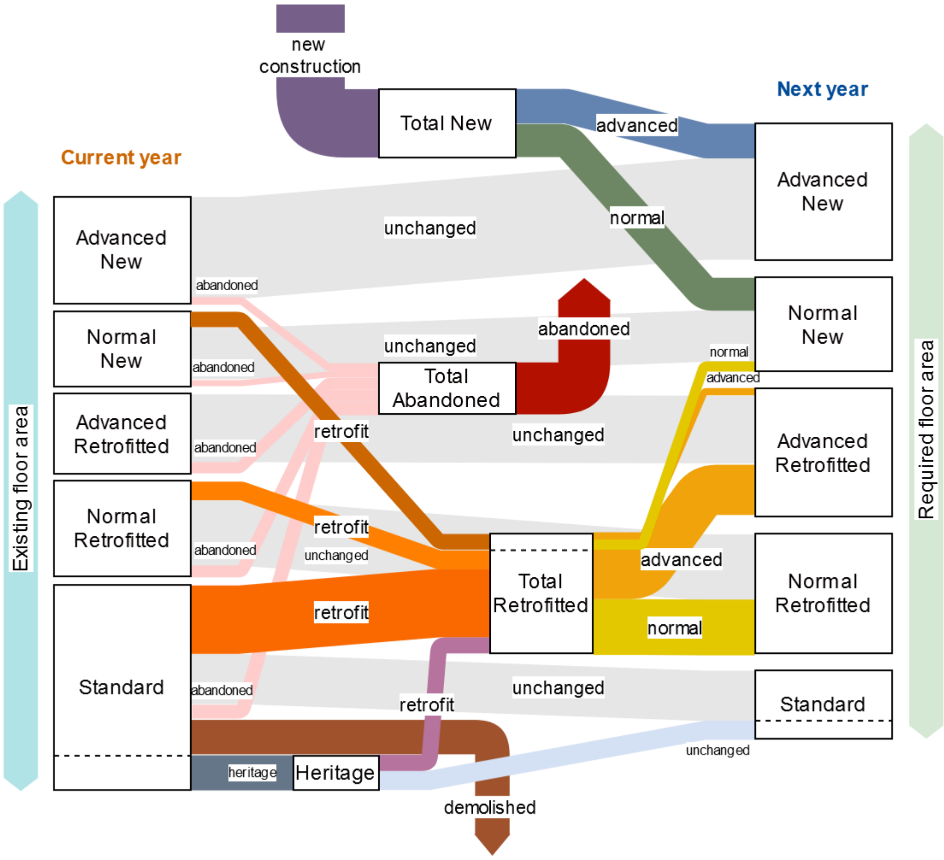


Figure 14. Yearly floor area dynamics of the HEB model.

The demolished floor area is calculated using region-specific demolition rates. After subtracting the demolished floor area from the existing total, the remaining existing floor area is classified into different building vintages. Similarly, the retrofitted floor area is calculated by applying yearly changing region-specific retrofit rates to the total existing building stock. The retrofitted floor area is further classified into two types of floor area, such as advanced retrofitted floor area and normal retrofitted floor area. For each of the regions, the share of retrofitted and advanced retrofitted floor area is different and furthermore, the share of advance retrofitted, advance new and retrofitted floor area vary under different scenarios. The floor area from the new constructions is classified into two types of building vintages namely, new and advanced new. Similar to the retrofitted floor area, the share of advance new floor area also varies under different scenarios.

3.1.2.4 Energy calculation

The energy consumption due to heating and cooling depends on the floor area. Thus, in the HEB model, the energy consumption is calculated after the year-specific floor areas calculations. The key input required to calculate the energy consumption of heating and cooling is the average consumption data of heating and cooling which is used from data reported in the literature for each of the regions, climate zone and building type as different building vintages has different consumption requirement. Therefore, different vintage types are modelled with assuming different energy intensity (denoted with subscript *v*). Furthermore, the values also depend on the scenarios (denoted with subscript *s*). Energy intensity is multiplied with the corresponding floor area to determine the heating and cooling energy consumption of the stock:

$$HCE_{r,c,u,b,t,Y,v,s} = TFA_{r,c,u,b,t,Y} \cdot EUhc_{r,c,u,b,t,v,s}$$

Equation 12

$HCE_{r,c,u,b,t,Y,v,s}$ *[kWh/year]* is the total heating and cooling energy demand of buildings with vintage type *v,* in scenario *s*, building type *t* in region *r and* climate zone *c* in year *Y*,

$TFA_{r,c,u,b,t,Y}$ *[m²]* is the total urban/rural floor area of building category *b* and building type *t* in region *r and* climate zone *c* in year *Y*,

$EIhc_{r,c,u,b,t,v,s}$ *[kWh/m²/year]* is the heating and cooling energy intensity of buildings with vintage type *v,* in scenario *s*, building type *t* in region *r and* climate zone *c*.

After calculating the detailed energy consumption, the data can be summed up to arrive at region-specific, yearly aggregated results in a given scenario:

$$Total\ Energy_{r,Y,s} = \sum_{c}\sum_{u}\sum_{b}\sum_{t}\sum_{v} Total\ Energy_{r,c,u,b,t,Y,v,s}$$

Equation 13

3.1.2.5 Hourly calculation

The reduction of the yearly total energy demand of buildings is one of the key aspects to achieve climate neutrality in the building sector. However, when integrated with the whole energy system it is not only the yearly demand, but its distribution also that becomes important. With the deeper penetration of renewable energy systems, the hourly variability of the energy supply mix can be less optimized, hence it is important when and how much buildings consume. Therefore, an additional methodology has been developed in HEB to disaggregate the yearly energy demand into hourly. There is a wide range of studies in the scientific literature that provides specific techniques to determine the hourly demand profile of buildings. Lindberg et al. (2019) provides an extensive overview of such methods for heating and cooling, while Fuentes et al. (2018) published an overview for hot water methods. Lindberg et al. (2019) classifies the approaches into Top-down and Bottom-up based on the data collection and the extrapolation/aggregation types. In a Bottom-up method hourly demands are usually calculated on a single building level (usually through Building Energy Simulation tools) with stochastic occupancy models, and different exemplary building types. The results are extrapolated to the building stock level. In a Top-down approach usually aggregated grid-level sectoral data is collected and simplified models are derived to predict the load distribution within the year. In the first case if the data is extrapolated, it needs to be validated against existing sectoral time-series data, while in the second case the requirement for the statistical data is evident. As no data is available for all the regions used in HEB, existing published methods are used to apply the heating, cooling and hot water energy demand profiles to the yearly demand. The energy demand of buildings for heating and cooling shows similar behavior, while the energy demand for hot water production is somewhat different patter, therefore it is discussed separately. Many studies focus on the electricity demand profile (such as the papers of Czétány et al. (2021) or Palzer and Henning (2014)) which is also a key area for the building energy demand, but the available data covers mostly the energy demand of appliances which is out of scope of HEB. However, with the deeper penetration of heat pumps, larger share of the building energy demand will be covered by electricity which makes these studies very relevant in future research.

Heating and cooling: Heating and cooling energy demand has one of the largest share in most developed regions within the total energy demand of buildings. At the same time its distribution within the year mostly depends on the weather conditions. Recent studies conclude that among weather features, the ambient temperature is the most important when determining the energy demand. Lindberg et al. (2019) for example highlight that wind and solar radiation is less important (base on previous works of the authors). In their model they apply a linear-constant function to calculate the heat demand from the ambient temperature. In principle the same approach is used by Henning and Palzer (2014) but they assume that there is zero demand if the ambient temperature goes above a fixed set temperature. Dotzauer (2002) developed a more sophisticated piecewise-linear regression model based on district heating data and he also concluded that solar radiation and wind are not important. Furthermore, he identifies that de development of load prediction models should focus more on better quality weather forecasts than on improving the advanced load prediction algorithms. Pedersen et al. (2008) developed a linear model based on a large sample of measured data to predict heat and electricity demand of buildings. The model includes a temperature-dependent and a temperature-independent region for the heat energy prediction. However, they conclude that the temperature-independent data reflects mostly the hot water energy demand of the observed buildings. Sachs et al. (2019) developed a global (spatially and temporally resolved) model for determining the heating and cooling energy demand of the residential sector. Similar to the previous studies they also use a simple linear regression between the ambient temperature and the heat demand. Mutschler et al. (2021) analyzed fine resolution building measurement data and weather station observations in the Swiss context and they also justified the high correlation of heating and air conditioning energy to ambient temperature. Based on the literature we can conclude that a simple model using only the ambient temperature as an input is sufficient in most of the cases to predict the hourly distribution of the yearly heating and cooling energy demand over the year.

Therefore, characteristic hourly ambient temperature data has been collected and calculated for each climate zone and region of HEB. This results in a dataset containing temperature data in 8760 hours of the year in 195 geographical areas of the World. Based on this dataset the hourly energy demand can be calculated with the following methodology.

Heating and cooling degree-hours are calculated based on an arbitrary chosen set-point temperature. The set temperature is usually lower than the required indoor temperature both in case of heating and cooling, because additional energy is captured in buildings due to solar radiation and other factors (like internal heat gain of occupants or appliances). This additional energy covers a certain part of the heating energy demand thus resulting in a lower threshold for heating energy demand. On the other hand, this means an extra load for cooling systems in summer (increased cooling demand), as if the required temperature was set to a lower level. Heating-degree-hours and cooling-degree-hours are calculated as:

$$HDH_i = T_{set,\,h} - T_{amb,\,i} \; if \; T_{amb,\,i} < T_{set}$$
$$0 \; if \; T_{amb,\,i} \geq T_{set,\,h}$$

Equation 14

$$CDH_i = T_{amb,\,i} - T_{set,\,c} \; if \; T_{amb,\,i} > T_{set}$$
$$0 \; if \; T_{amb,\,i} \leq T_{set,\,h}$$

Equation 15

where HDH_i (Hour × °K) is the Heating-degree-hour value in hour-of-the-year i; CDH_i (Hour × °K) is the Cooling-degree-hour value in hour-of-the-year i; $T_{set,\, h}$ (°C) is the setpoint temperature for heating, defaults to 18°C based on literature values; $T_{set,\, c}$ (°C) is the setpoint temperature for cooling, defaults to 22°C based on literature values; $T_{amb,\, i}$ (°C) is the ambient temperature in hour-of-the-year i.

$$h_i = HDH_i \; if \; T_{mean,\, day(i)} < T_{base,\, h}$$
$$0 \; if \; T_{mean,\, d(i)} \geq T_{base,\, h}$$

Equation 16

$$c_i = CDH_i \; if \; T_{mean,\, day(i)} < T_{base,\, c}$$
$$0 \; if \; T_{mean,\, d(i)} \geq T_{base,\, c}$$

Equation 17

where h_i (Hour × °K) is the filtered heating-degree-hour factor in hour-of-the-year i; c_i (Hour × °K) is the filtered cooling-degree-hour factor in hour-of-the-year i; HD_i (Hour×°K) is the Heating-degree-hour value in hour-of-the-year i; CD_i (Hour×°K) is the Cooling-degree-hour value in hour-of-the-year i; $T_{mean,\, day(i)}$ (°C) is the daily mean temperature of in hour-of-the-year i; $T_{base,\, h}$ (°C) is the base temperature for the HDH calculation, defaults to 18°C; $T_{base,\, c}$ (°C) is the base temperature for the CDH calculation, defaults to 22°C.

The temperature factor can be calculated as the 0-1 normalization of h_i and c_i over the total in the year:

$$Tf_{h,} = h_i \,/\, \Sigma h_i$$

Equation 18

$$Tf_{c,} = \;/\, \Sigma c_i$$

Equation 19

where $Tf_{h,i}$ (-) is the temperature factor for the heating energy distribution in hour-of-the-year i; $Tf_{c,i}$ (-) is the temperature factor for the cooling energy distribution in hour-of-the-year i; h_i (Hour × °K) is the filtered heating-degree-hour factor in hour-of-the-year i; c_i (Hour × °K) is the filtered cooling-degree-hour factor in hour-of-the-year i.

Heating systems are operated by temperature sensors in most of the developed regions. On the other hand, cooling systems are often operated by humans, therefore the demand occurs only if the building is occupied. Therefore specific stochastic occupancy schedules have been collected from the ASHRAE Handbook (ASHRAE, 2015) to determine the fraction of occupants using the buildings. Examples of such schedules are illustrated on Figure 15 (residential buildings) and Figure 16 (office buildings). Each commercial and public building has a different typical occupancy schedule.

Buildings do not respond directly to outdoor air temperature change, because the construction materials usually have high heat store capacity which results in a "thermal inertia" of the building.

Therefore, in climates with seasonality the solar radiation during the day can be utilized to cover the night energy demand in the low-heating season. This results in a period, when the ambient temperature is lower than the required indoor temperature but there is no heating demand. To express this in the hourly distribution, only those days are considered for determining the heating degree hours, when the daily mean temperature is lower than a certain base temperature:

$$h_i = HDH_i \; if \; T_{mean,\,day(i)} < T_{base,\,h}$$
$$0 \; if \; T_{mean,\,d(i)} \geq T_{base,\,h}$$

Equation 20

$$c_i = CDH_i \; if \; T_{mean,\,day(i)} < T_{base,\,c}$$
$$0 \; if \; T_{mean,\,d(i)} \geq T_{base,\,c}$$

Equation 21

where h_i (Hour×°K) is the filtered heating-degree-hour factor in hour-of-the-year i; c_i (Hour×°K) is the filtered cooling-degree-hour factor in hour-of-the-year i; HD_i (Hour×°K) is the Heating-degree-hour value in hour-of-the-year i; CD_i (Hour×°K) is the Cooling-degree-hour value in hour-of-the-year i; $T_{mean,\ day(i)}$ (°C) is the daily mean temperature of in hour-of-the-year i; $T_{base,\ h}$ (°C) is the base temperature for the HDH calculation, defaults to 18°C; $T_{base,\,c}$ (°C) is the base temperature for the CDH calculation, defaults to 22°C.

The temperature factor can be calculated as the 0-1 normalization of h_i and c_i over the total in the year:

$$Tf_{h,} = h \; / \; \Sigma h_i$$

Equation 22

$$Tf_{c,} = c_i \; / \; \Sigma c_i$$

Equation 23

Heating systems are operated by temperature sensors in most of the developed regions. On the other hand, cooling systems are often operated by humans, therefore the demand occurs only if the building is occupied. Therefore specific stochastic occupancy schedules have been collected from the ASHRAE standard series (ASHRAE, 2015) to determine the fraction of occupants using the buildings. Examples of such schedules are illustrated on Figure 15 (residential buildings) and Figure 16 (office buildings). Each commercial and public building has a different typical occupancy schedule.

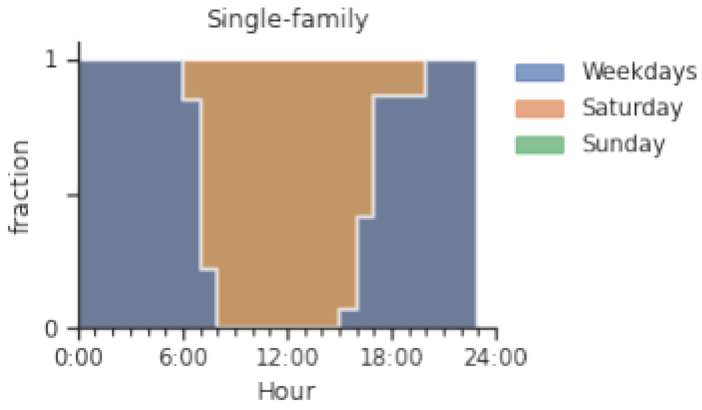


Figure 15. Occupancy schedule of residential buildings.

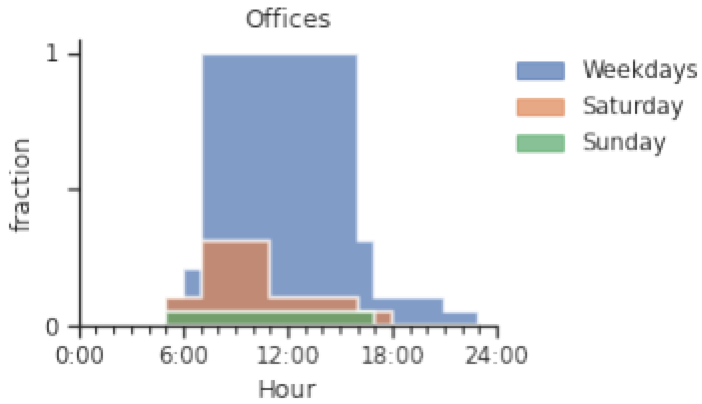


Figure 16. Occupancy schedule of office buildings.

The schedule factor is determined as:

$$s_{c,\,i} = Sch_c\,(i \bmod 24,\, \text{daytype}(i))$$

Equation 24

where $s_{c,\,i}$ (-) is the schedule value in hour-of-the-year i; $Sch_c(H,\,T)$ (-) is the occupancy schedule of hour-of-the-day H and day type T; i mod 24 is the hour-of-the-day corresponding to hour-of-the-year i calculated by the remainder of the integer division (modulo operator); daytype(i) is the type of day within the week corresponding to hour-of-the-year i (either of Weekdays, Saturday, or Sunday).

Then the value is normalized over the total within the year:

$$Sf_{c,\,i} = s_{c,\,i} \,/\, \Sigma s_{c,\,i}$$

Equation 25

where $Sf_{c,\,i}$ (-) is the (normalized) schedule factor in hour-of-the-year i; $s_{c,\,i}$ (-) is the schedule value in hour-of-the-year i.

Finally, heating and cooling profile values are determined using the following equations:

$$E_{h,i} = E_{h,year} \times Tf_{h,i}$$
$$E_{c,i} = E_{c,year} \times Tf_{c,i} \times Sf_{c,i}$$

Equation 26

where $E_{h,i}$ (kWh) is the heating energy demand in hour-of-the-year i; $E_{c,i}$ (kWh) is the cooling energy demand in hour-of-the-year i; $E_{h,year}$ (kWh) is the total yearly heating energy demand; $E_{c,year}$ (kWh) is the total yearly cooling energy demand; $Tf_{h,i}$ (-) is the temperature factor for the heating energy distribution in hour-of-the-year i; $Tf_{c,i}$ (-) is the temperature factor for the cooling energy distribution in hour-of-the-year i; $Sf_{c,i}$ (-) is the schedule factor in hour-of-the-year i.

Hot water: Unlike the heating and cooling energy demand, the energy demand to produce hot water is rather dependent on user behavior. In their review Fuentes et al. (2018) analyzed a large number of research studies on how to apply hot water consumption profiles in building energy performance analysis. In their work they concluded that the hot water energy demand is mainly influenced by two factors: mains temperature and the tapping cycle. Within this context mains temperature refers to the temperature of the water in the piping system which is usually buried into the ground to supply buildings. Since the water needs to be heated from this temperature to the constant required temperature in the storage tank or directly out of the tap, the energy to cover this heat difference is in correlation with the mains temperature. As the pipes are below the ground, the mains temperature usually does not follow the daily fluctuation of the air temperature. Instead, it is in closer correlation to the daily mean temperature. Most of the studies assume a sinusoid curve within the year (see Figure 17) to describe seasonal dependency of the mains temperature from the ambient temperature. One of the most widely used equation was developed by Burch and Christensen (2007). They tested and validated the method in the context of the USA. The method was also applied by Hendron et al. (2004) with specific parameters, both neither of the papers provide information on how much the method can be used in different climate zones of the world. Fuentes et al. (2018) modified the original equation parameters of Burch and Christensen (2007) and Hendron et al. (2004) to comply with their study having an example building in a Spanish climate. They conclude that- after adjustment - the method can be extended to other climates as well.

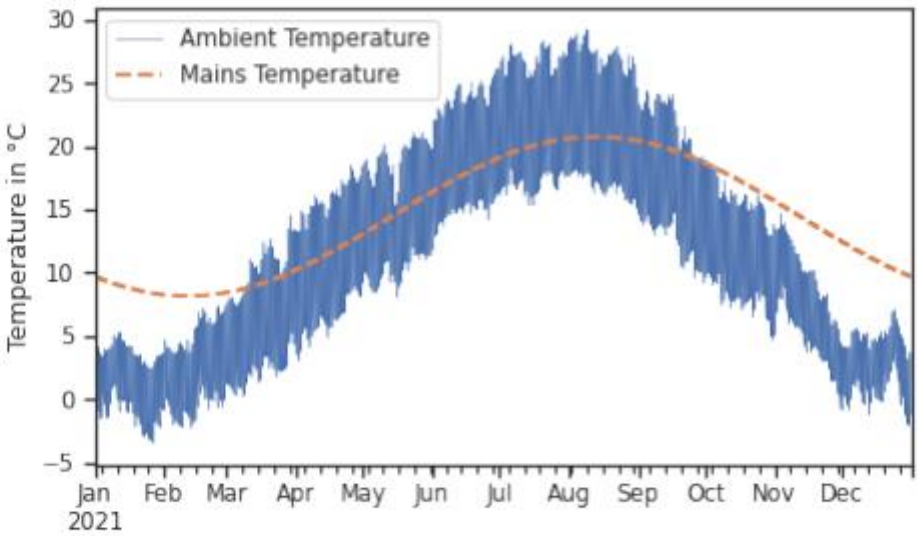


Figure 17. Example of water mains temperature calculation based on Burch and Christensen (2007)*.*

Tapping cycle refer to the hot water volume usage within a day. Standardized cycles are widely used in the industry to qualify products (like heaters and taps). Also stochastic models exist that are widely applied in building energy simulation tools. Such well justified models are provided by the ASHRAE standards (ASHRAE, 2015) and are also applied in HEB. These are expressed as hot water "schedules" specific for each building type and day type (weekday or weekend). Figure 18 and Figure 19 show examples of such schedules applied in HEB for residential and office buildings. Recent studies conclude that additionally to the previous factors, the volume of hot water also depends on a yearly seasonality, but the authors conclude that the reason is rather cultural than climate-specific (people go on holiday in summer), therefore this effect is neglected in the current model.

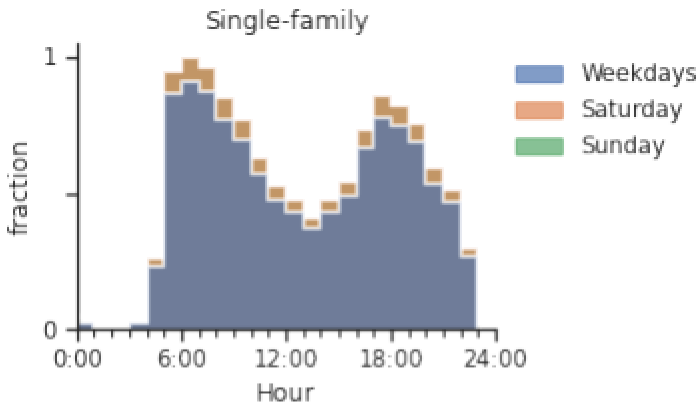


Figure 18. Hot water usage schedule of residential buildings.

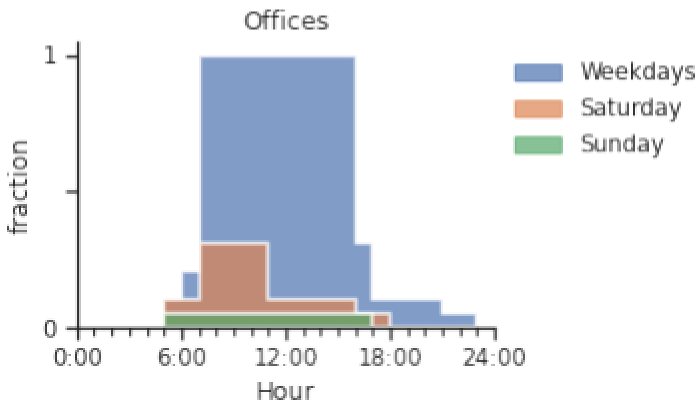


Figure 19. Hot water usage schedule of office buildings.

Consequently, the hot water profile is calculated based on two input data, the ambient air temperature and the hot water schedule. The mains temperature can be calculated with the following equation:

$$T_{mains,\,i} = T_{amb,} + \_T_{offset} + ((R \times \_T_{amb,max}) / 2) \times \sin(\omega \times t_i + \varphi)$$

Equation 27

$$\Delta T_{offset} = c \times \begin{cases} 6 & if \quad T_{amb,avg} < 68F \\ 6 \times \dfrac{74 - T_{amb,avg}}{74 - 68} & if \quad 68F < T_{amb,avg} \leq 74F \\ 0 & if \quad T_{amb,avg} \geq 74F \end{cases}$$

Equation 28

$$R = c \times \begin{cases} 0.4 + 0.005 \times (T_{amb,avg} - 68) & if \quad T_{amb,avg} < 68F \\ 0.4 & if \quad T_{amb,avg} \geq 68F \end{cases}$$

Equation 29

$$c = \begin{cases} \dfrac{1 - \sigma}{1 - 0.5} & if \quad \sigma > 0.5 \\ 1 & if \quad \sigma \leq 0.5 \end{cases}$$

Equation 30

$$\sigma = \Delta T_{daily,max} \, / \, (T_{amb,max} - T_{amb,min})$$

$$\omega = 360 / 365$$

$$t_i = doy_i - 15 - L$$

$$doy_i = \lfloor i / 24 \rfloor + 1$$

Equation 31

$$L = \begin{cases} 35 - 1.0 \times (T_{amb,avg} - 44) \ \ if \ T_{amb,avg} < 68F \\ 11 \ if \ T_{amb,avg} \geq 68F \end{cases}$$

Equation 32

$$\varphi = (-360 / 12) \times (n_{warmest\ month} - 1) + 90$$

Equation 33

where $T_{mains,\ i}$ (°F) is the mains (inlet) water temperature in hour-of-the-year i; $T_{amb,avg}$, $T_{amb,min}$, $T_{amb,max}$ (°F) are the average, minimum, and maximum ambient temperatures in the year; ΔT_{offset} (°F) is the temperature difference between the average yearly ambient temperature and the average yearly main temperature due to other factors than the ambient air temperature (e.g. solar radiation); R (-) amplitude parameter of the sinusoid curve; $\Delta T_{amb,max}$ (°F) is the maximum difference between monthly average temperatures within the year (e.g. average in July and average in January); ω (°/day) is the degrees corresponding to one day in a year; t_i (days) is the dependent variable in the main equation; φ (°) is the phase shift of the sinusoid curve that is calculated based on the location (1-12) of the warmest month within the year (maximum of the sinusoid); c (-) is the correction factor for climates with non-typical seasonality; σ (-) is the ratio of the maximum of daily temperature fluctuations and the yearly temperature fluctuation within the year; doy_i (-) is the day-of-the-year corresponding to the hour-of-the-year i. It can be calculated as the floor division of i by 24 (hours in a day) plus 1; L (days) is the phase lag between the mains temperature and the ambient temperature due to thermal inertia of the ground.

Most of the specific factors, are taken from Hendron et al. (2004), however, some modification have been introduced compared to the original equation of Burch and Christensen (2007) if the yearly average ambient temperature is higher than 20°C (68F): offset temperature is assumed to decrease. Amplitude R is maximized at 0.4. A correction factor c is used to reduce ΔT_{offset} and R in climates where winter-summer seasonality is not typical (where the daily temperature fluctuation is close to the yearly temperature fluctuation). The phase lag L is minimized at 11 days. Absolute limit of 0°C (32F) - freezing point of water - is set for the $T_{mains,\ i}$ in all cases. Note that the mains temperature calculation is carried out using Fahrenheit (F) values due to the compatibility of the cited papers, however, the output of the calculation is converted into Celsius (°C).

After calculation of the mains temperature, the heat factor can be determined using the temperature difference between the required water temperature and the water temperature:

$$w_i = T_w - T_{mains,\ i}$$
$$T_{fw,\ i} = w_i / \Sigma w_{c,\ i}$$

Equation 34

where w_i (°C) is the temperature difference that needs to be covered by the hot water heater in hour-of-the-year i; T_w (°C) is the desired tap water temperature (defaults to 44°C); $T_{mains,\ i}$ (°C) is the mains (inlet) water temperature in hour-of-the-year i; $Tf_{w,i}$ (-) is the temperature factor of hot water energy demand for hour-of-the-year i.

Hot water schedules are calculated the same way as in the case of cooling but using different schedule values. After determining the temperature factor and the schedule factor, the hot water energy demand can be calculated in each hour of the year with the following equation:

$$E_{w,i} = E_{w,year} \times Tf_{w,i} \times Sf_{w,i}$$

Equation 35

where $E_{w,i}$ (kWh) is the hot water energy demand in hour-of-the-year i; $E_{w,year}$ (kWh) is the total yearly energy demand of hot water production; $Tf_{w,i}$ (-) is the temperature factor of hot water energy demand for hour-of-the-year i; $Sf_{w,i}$ (-) is the schedule factor of hot water usage in hour-of-the-year i calculated the same way as for cooling.

Time-zone correction: The specific schedules (usage profiles) depend on the daily routine of people, which is highly influenced by the timezone. Moreover, the ambient air temperature also correlates with the local time, since no solar radiation occurs before sunrise. This effect is more important if a geographical area is large towards East-West (large Longitude difference), and the demand in the East region is shifted from the West region. Therefore, in HEB a time-zone correction is applied to consider this effect. To calculate the weighted demand for a specific region, the heating, cooling and hot water profiles are shifted according to the time zones in the region. The shifted demand curves are weighted and averaged which results in a smoothed profile specific for that region.

Weights can be any arbitrary data which correlates with the amount of building-related energy used in that region. (For example population within that time zone can be used as a proxy to assume the share of building stock within that time zone). The calculation can be expressed with the following equation:

$$E_{r,i} = (\Sigma E_{r,z,i} + \text{offset}(z) \times w_{r,z}) \,/\, \Sigma w_{r,z}$$

Equation 36

where $E_{r,UTCi}$ (kWh/m^2) is the weighted energy demand (heating, cooling or hot water) in region r and UTC hour-of-the year $UTCi$; $E_{r,z,i}$ (kWh/m^2) is the energy demand (heating, cooling or hot water) in region r, time zone z and hour-of-the-year i; $w_{r,z}$ (-) is the weight of time zone z within region r; offset(z) (hours) is the offset of time-zone z from UTC.

The result is expressed in UTC time, which makes results of HEB for each region and the World comparable. Note that all calculations are done on each series of ambient temperature data, therefore specific profiles are developed for each region and climate zone of HEB. However, to avoid ambiguity the region and climate zone indices are not indicated in the equations.

Climate classification: The climate zones used in the HEB and BISE model were derived using the NASA's Goddard Earth Sciences (GES) Data Information Services Centre (DISC) MERRA-2 (Modern-Era Retrospective analysis for Research and Applications) reanalysis dataset (Gelaro et al., 2017). The selected gridded (raster) dataset covers a 11-year period (between 2010 and 2020) and has hourly temporal resolution. During the classification process, the gridded values of ambient air temperature and relative humidity were applied. Based on the 11-year long time-series of variables, one annual profile were generation in each grid point, which was created to represent the one decadal mean patterns of these meteorological variables across the globe. Following the methodology of Petrichenko (2014), the classification relied on four parameters: cooling degree days (CDD), heating degree days (HDD), monthly mean air temperature and relative humidity of the warmest month. The base temperature for the estimation of the CDD and HDD values, 22°C and 18°C are used. These are very typical values in the literature (Sadeqi et al., 2022).

In order to have an 'a priori' understanding on the data, density functions as well as Box and Whiskers diagrams of the variables were generated, separately for each HEB-region. As a next step, a K-means clustering was performed during which the optimal number of the clusters was determined by the elbow method. Then the resultant classes were adjusted with population density data (GPW dataset; CIESIN, 2018) to filter small and less populous zones and to have more meaningful categories. As a result, the climate classification includes 19 different zones. Based on our classification, there are areas where only heating, only cooling, heating and cooling, dehumidification and absence of heating and cooling (Table 3). The most grids were classified into the 'Only heating (Very high demand)', 'Cooling and Dehumidification (Moderate demand)' and 'Heating, cooling and dehumidification (Low and moderate heating and cooling demand)' categories (Figure 20).

Table 3. Developed climate classification system used in the HEB and BISE models.

Category	CDD [°C]	HDD [°C]	$RH_{warmest}$ [%]	$T_{warmest}$ [°C]
1. Only heating (Very high heating demand)	< 100	>= 5000	-	-
2. Only heating (High heating demand)	< 100	>= 3500 & < 5000	-	-
3. Only heating (Moderate heating demand)	< 100	>= 1000 & < 3500	-	-
4. Only heating (Low heating demand)	< 100	>= 100 & < 1000	-	-
5. Heating and cooling (High heating and low cooling demand)	>= 100 & < 500	>= 3500 & < 5000	< 75	< 25
6. Heating and cooling (Moderate heating and low cooling demand)	>= 100 & < 500	>= 1000 & < 3500	< 75	< 25
7. Heating and cooling (Moderate heating and cooling demand)	>= 500 & < 2500	>= 1000 & < 3500	< 75	< 25
8. Heating and cooling (Low heating and high cooling demand)	>= 2500 & < 4000	>= 100 & < 1000	< 75	< 25
9. Heating and cooling (Low heating and moderate cooling demand)	>= 500 & < 2500	>= 100 & < 1000	< 75	< 25
10. Heating and cooling (Low heating and cooling demand)	>= 100 & < 500	>= 100 & < 1000	< 75	< 25
11. Only cooling (Very high cooling demand)	>= 4000	< 100	< 75	< 25

12. Only cooling (High cooling demand)	>= 2500 & < 4000	< 100	< 75	< 25
13. Only cooling (Moderate cooling demand)	>= 500 & < 2500	< 100	< 75	< 25
14. Only cooling (Low cooling demand)	>= 100 & < 500	< 100	< 75	< 25
15. Cooling and dehumidification (High cooling demand)	>= 2500 & < 4000	< 100	>= 75	>= 25
16. Cooling and dehumidification (Moderate cooling demand)	>= 500 & < 2500	< 100	>= 75	>= 25
17. Cooling and dehumidification (Low cooling demand)	>= 100 & < 500	< 100	>= 75	>= 25
18. Heating, cooling and dehumidification (Low and moderate heating and cooling demand)	>= 100 & < 2500	>= 100 & < 3500	>= 75	>= 25
19. Minor heating and cooling (Low heating and moderate cooling demand)	<= 100	<= 100	-	-

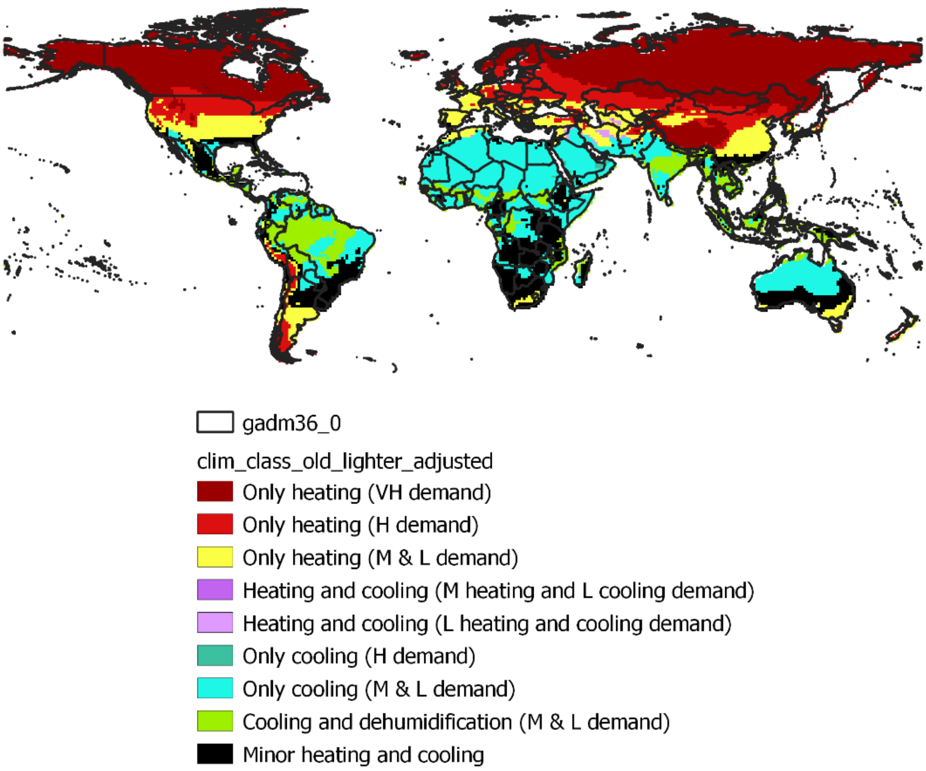


Figure 20. Spatial distribution of the developed climate classification used in the HEB and BISE models.

3.1.3. Implementation

The most recent version of the HEB model is developed in Python programming language using the PyData ecosystem to handle large datasets. This ecosystem ensures quite large flexibility amongst modelling parameters, and the diversity of input data and its granularity can be properly handled. This model is not an open access model yet.

3.2 Building Integrated Solar Energy (BISE) model:

3.2.1. General description

The BISE model has been developed to estimate the largest solar electric and thermal energy production of hybrid PV/T collectors that is technically feasible on the rooftops of residential and tertiary buildings. The BISE is a simulation model with bottom-up modeling approach and was interpreted in Python programming language. This closed-licensed global model considers the same 11 focus regions (and 31 countries) as the HEB model. The disaggregation strategy in the model is also identical to the HEB given that the buildings in the different regions are split as per climate zones, built environment (e.g., urban, rural and slum), type (e.g., residential and commercial/public), function (e.g., single family, multifamily, educational, hospitals, hotels and restaurants, retails, offices and other) and vintage type (e.g., existing, new, retrofitted, advanced new and advanced retrofitted).

Due to the high spatial and temporal representation of input data, the BISE provides high-granularity simulations with hourly time step. The fine temporal resolution of the outputs ensures capturing different heat and power generation characteristics, ranging from hourly to annual level. In order to represent the most crucial period in terms of the transition of the energy system to a climate resilient path, a modeling time frame during the years between 2022 and 2060 was selected. For assessing different policy interventions on the utilization of solar technology during the above period, six scenarios were incorporated into the model.

The outputs are generated by the BISE in netCDF format that scientifically used to store multilayered gridded data with favorable compression rate. NetCDF files may easily be postprocessed with the combination of GIS (Geographic Information System) tools and Python packages (e.g., Numpy, Matplotlib, Pandas). For our analysis, therefore, we apply different geoprocessing techniques (e.g., geostatistics, zonal statistics, geodata extraction) and Python (“PyGIS” technique) to guarantee a great basis on the later visualization purposes.

Due to the flexible modeling design, the outputs of the BISE are suitable to easily be compared with other modeling products. Comparing them, for example, with simulations of energy demand models could help to gain insight on the possibility of achieving energy balance between the supply and demand sides at building level, utilizing solely solar thermal and electric energy. Furthermore, there is an opportunity to analyze the impact of different actions (taken on both sides) on reaching net zero building energy level, and also to identify challenges (e.g., energy storage capacity) that could possibly decelerate the transition to a carbon-neutral future. Formerly, the BISE model has been interlinked successfully with the HEB and BUENAS models to inspect the annual energy balance for heating, cooling, hot water and appliances as well as to estimate the areal probability of spreading NZEBs by 2050.

3.2.2. Calculation procedure

The computational core of the BISE model was designed to transcript the physical processes (e.g., the energy conversion of PV/T collectors) in the form of different mathematical formulas. These equations constitute two groups, separately for calculating of the thermal and electric energy production. The calculation part for the electric energy production follows the logic applied in many previous studies (e.g., Homerenergy, 2021; Mainzer et al., 2017; Mangiante et al., 2020).

Furthermore, they are completed with the mathematical interpretations of roof area dynamics and utilization parameters for PV/T collectors. First, these roof-related equations will be presented. Among the building rooftop characteristics, it is essential to estimate the total roof area (RA_{total}; m). As it will be discussed in the introduction of the inputs (see Section 3.2.2.), RA_{total} is quantified by means of GIS-based data processing and valid for the initial year of the simulation period. For other years, the calculation of this variable is based on floor area values (FA; m) projected originally in the HEB model.

$$RA_{total} = r_{roof\_to\_floor} \cdot FA$$

Equation 37

In the Equation 37, $r_{roof\_to\_floor}$ is a proportionality factor called roof to floor ratio [dimensionless]. The interannual change of RA_{total} is predicted for each (r) region, (c) climate zone, (u) urban type, (b) building category, (t) building type and (v) building vintage with the Equation 38.

$$RA_{total_{r,c,u,b,t,v}} = RA_{total_{2022,r}} \cdot \frac{FA_{r,c,u,b,t,v}}{FA_{2022,r,c,u,b,t,v}}$$

Equation 38

In order to derive that roof area available for solar system's installation ($RA_{available}$; m), there is a need to give an assumption on the so-called utilization factor (U_F; dimensionless). U_F, as it can be seen in the Equation 39, directly includes the effects of construction restrictions (C_{CON}), number of protected buildings (C_{PROT}), shading effects (C_{SH}), service areas (C_{SA}), losses due to roof orientation (C_{AZ}), roof tilting (C_{SL}), separation of panels/collectors (C_{GCR}), fraction of PV panels (C_{PV}) and fraction of thermal collectors (C_{TH}) [all dimensionless] on the area suitability.

$$U_F = C_{CON} \cdot C_{PROT} \cdot C_{SH} \cdot C_{SA} \cdot C_{AZ} \cdot C_{SL} \cdot C_{GCR} \cdot C_{PV} \cdot C_{TH}$$

Equation 39

Then U_F is applied as a reduction factor for RA_{total} to generate $RA_{available}$ in the following way:

$$RA_{available} = RA_{total} \cdot U_F$$

Equation 40

The year-to-year dynamic of $RA_{available}$ for each (r) region, (c) climate zone, (u) urban type, (b) building category, (t) building type and (v) building vintage is computed identically to the Equation 38, employing $RA_{available}$ instead of RA_{total} in the same logic.

Once $RA_{available}$ is available, the effective area of the installed PV/T system ($A_{PV/T\ syst}$) can be calculated as follows:

$$A_{PV/T\ syst} = RA_{available} \cdot F_{aperture}$$

Equation 41

where $F_{aperture}$ (aperture factor of the installed PV/T systems; dimensionless) is equal to 0.9 (RETScreen, 2020). Naturally, the $A_{PV/T\ syst}$ has the same disaggregation (i.e., by r, c, etc.) as $RA_{available}$.

However, the formulas for PV/T electric and thermal outputs strongly build upon the radiation income received by the PV/T collector, this amount of energy is dependent firstly on that what fraction of the sunlight is attenuated coming through the atmosphere. This loss is expressed in the BISE model via the clearness index (K; dimensionless).

$$K = \frac{I_{Glob,h}}{I_{TOA}}$$

Equation 42

where $I_{Glob,h}$ is the surface (or the horizontal component of) global radiation and I_{TOA} is the incoming shortwave radiation at the top of the atmosphere [both in W/m^2]. Both $I_{Glob,h}$ and I_{TOA} is used as meteorological inputs in the model. Based on K and $I_{Glob,h}$, the diffuse component of the radiation on the horizontal surface ($I_{D,h}$; W/m$_2$) is computed with the Erbs' model (Erbs et al., 1982):

$$I_{D,h} = I_{Glob,h} \times \begin{cases} 1 - 0.09K & for\ K \leq 0.22 \\ 0.9511 - 0.1604K + 4.388K^2 - 16.638K^3 + 12.336K^4 & for\ 0.22 < K \leq 0.80 \\ 0.165 & for\ K > 0.80 \end{cases}$$

Equation 43

The direct (or beam) radiation on the horizontal surface ($I_{B,h}$) can be calculated, by definition, as the difference of $I_{Glob,h}$ and $I_{D,h}$.

$$I_{B,h} = I_{Glob,h} - I_{D,h}$$

Equation 44

Unlike for other radiation components, it is not necessary to compute the reflected radiation for the horizontal surface, but the amount of energy received by the PV/T collector ($I_{R,tilt}$; W/m^2) can be estimated directly. To do so, the tilt of the PV/T collector (β; in degrees) is needed to be computed, which varies by regions in the model. The regional values of β are represented as ideal tilt angles that ensure the highest radiation income on annual basis. As the Equation 45 indicate, the ideal β values in the BISE model depend on the latitudinal extension (latitude: φ; degrees) of a given region and is expressed by polynomial equations, separately for the northern and the southern hemisphere (Jacobson and Jadhav, 2018).

$$\beta_{NORTH} = 1.3793 + \varphi[1.2011 + \varphi(-0.14404 + 0.000080509\varphi)]$$

$$\beta_{SOUTH} = -0.41657 + \varphi[1.4216 + \varphi(0.024051 + 0.00021828\varphi)]$$

Equation 45

Once the β values are known, $I_{R,tilt}$ is given by the following formula:

$$I_{R,tilt} = \frac{\rho}{2} \cdot I_{Glob,h} \cdot (1 - cos\beta)$$

Equation 46

where ρ is the surface radiation [fixed at 0.2; dimensionless] and $I_{Glob,h}$ is the same as in the Equation 42.

In the next steps, the model computes the radiation components received by the tilted PV/T collectors with the help of the $I_{B,h}$ and $I_{D,h}$ values. To quantify the beam radiation on the tilted plane ($I_{B,tilt}$; W/m^2), it is indispensable to gain insight on the temporal variation of the Sun's path on the sky at a given location. The position of the Sun relative to the analyzed geographical area is given with such parameters as the incidence angle of solar ray (θ; degrees), solar zenith angle (θ_z; degrees), hour angle (ω; degrees), declination (δ; degrees) and solar azimuth angle (γ_S). Therefore, these astronomical variables and $I_{B,tilt}$ are calculated as follows:

$$\delta = 23.45 \cdot \sin\left(360 \cdot \frac{284+DOY}{365}\right)$$

Equation 47

$$cos\theta_z = cos\varphi\ cos\delta\ cos\omega + sin\varphi\ sin\delta$$

Equation 48

$$cos\theta = cos\theta_z\ sin\beta + sin\theta_z\ sin\beta\ cos(\gamma_S - \gamma)$$

Equation 49

$$\gamma_S = \pm cos^{-1}\left(\frac{cos\theta_z\ sin\varphi - sin\delta}{sin\theta_z\ cos\varphi}\right)$$

Equation 50

$$I_{B,tilt} = I_{B,h} \cdot \frac{cos\theta}{cos\theta_z}(1 - y)$$

Equation 51

In the Equations above, $I_{B,h}$ is the result of Equation 44, β is the result of Equation 45, DOY is the day of the year, γ is the azimuth of the solar system [in degrees] and y is a factor considers losses from reflection in the atmosphere [dimensionless]. Since we assume south-facing solar panels, by definition, γ was set to 0°. Theoretically, ω varies between -180° and 180° during the day, increasing with 15° in each hour. In the Equation 50, the sign of the result is always identical with the sign of ω. As ω and the other astronomical variables change in harmony with the local time at a given geographical location, they are derived from the respective UTC and time zone by using a Python module named "Timezonefinder".

y in the Equation 10. is determined by analyzing θ thresholds (Yang et al., 2014).

$$y = \begin{cases} 0, & 0 \le \theta < 30° \\ 0.0006(\theta - 30), & 30 \le \theta < 40° \\ 0.006 + 0.0012(\theta - 40), & 40 \le \theta < 50° \\ 0.018 + 0.0029(\theta - 50), & 50 \le \theta < 60° \\ 0.047 + 0.0068(\theta - 60), & 60 \le \theta < 65° \\ 0.081 + 0.0098(\theta - 65), & 65 \le \theta < 70° \\ 0.13 + 0.0166(\theta - 70), & 70 \le \theta < 75° \\ 0.213 + 0.0276(\theta - 75), & 75 \le \theta < 80° \\ 0.351 + 0.047(\theta - 80), & 80 \le \theta < 85° \\ 0.586 + 0.0828(\theta - 85), & 85 \le \theta < 90° \end{cases}$$

Equation 52

The diffuse radiation on the tilted plane ($I_{D,tilt}$; W/m^2) can then be expressed by:

$$I_{D,tilt} = I_{D,h} \times \left[0.5 \cdot (1 + cos\beta) \cdot (1 - F_1) + \frac{a}{b} F_1 + F_2 \cdot sin\beta\right]$$

Equation 53

The algorithm for the $I_{D,tilt}$, therefore, includes $I_{D,h}$ from the Equation 43, β from the Equation 45, a=max(0; cos θ) and b=max(0.087; cos θ_z) terms and F_1, F_2 circumsolar brightening coefficients.

The F_1 and F_2 coefficients are estimated with the Perez's transposition model (Perez et al., 1990) in which the diffuse part of the solar radiation is influenced mostly by the distance travelled by the Sun's rays and the turbidity of the atmosphere. The latter is taken into consideration with the sky's clearness parameter (ε; dimensionless).

$$\varepsilon = \frac{\frac{I_{D,h} + I_{B,h}(cos\theta_z)^{-1}}{I_{D,h}} + \kappa\theta_z^3}{1 + \kappa\theta_z^3}$$

Equation 54

In the Equation 54, $I_{D,h}$ ($I_{B,h}$) is the output of Equation 43 (Equation 44) and κ is a constant (κ=1.041; Mainzer et al., 2017). For avoiding confusion, it must be highlighted that K and ε have, however, the same name but physically quite different meaning.

The travelled distance by the sunlight (relative to the shortest length) is estimated via the solar zenith angle (θ_z from Equation 48) and the air mass (AM, dimensionless) parameter (De Soto et al., 2006).

$$AM = \frac{1}{cos\ \theta_z + 0.5057(96.080 - \theta_z)^{-1.634}}$$

Equation 55

For solving the Equation 53, the sky's brightness (Δ; dimensionless) is needed to be quantified lastly. Δ is defined by comparing surface diffuse radiation ($I_{D,h}$) to Sun constant (I_0=1367 W/m^2):

$$\Delta = AM \cdot \frac{I_{D,h}}{I_0}$$

Equation 56

Then the F_1 and F_2 coefficients of Perez's model are computed by:

$$F_1 = F_{11} + F_{12} \cdot \Delta + F_{13} \cdot \theta_z$$
$$F_2 = F_{21} + F_{22} \cdot \Delta + F_{23} \cdot \theta_z$$

Equation 57

In the Equation 57, the $F_{11\rightarrow 23}$ values differ by the magnitudes of ε outputs (Table 4).

Table 4. Auxiliary table for the Perez's transposition model to determine coefficients based on ε values (Perez et al., 1990).

Criteria	F_{11}	F_{12}	F_{13}	F_{21}	F_{22}	F_{23}
$1 \leq \varepsilon < 1.065$	−0.008	0.588	−0.062	−0.060	0.072	−0.022
$1.065 \leq \varepsilon < 1.23$	0.130	0.683	−0.151	−0.019	0.066	−0.029
$1.23 \leq \varepsilon < 1.5$	0.330	0.487	−0.221	0.055	−0.064	−0.026
$1.5 \leq \varepsilon < 1.95$	0.568	0.187	−0.295	0.109	−0.152	−0.014
$1.95 \leq \varepsilon < 2.8$	0.873	−0.392	−0.362	0.226	−0.462	0.001
$2.8 \leq \varepsilon < 4.5$	1.132	−1.237	−0.412	0.288	−0.823	0.056
$4.5 \leq \varepsilon < 6.2$	1.060	−1.600	−0.359	0.264	−1.127	0.131
$6.2 \leq \varepsilon$	0.678	−0.327	−0.250	0.156	−1.377	0.251

Once all radiation components for the tilted plane are determined (i.e., $I_{R,tilt}$ from the Equation 46, $I_{B,tilt}$ from the Equation 51, $I_{D,tilt}$ from the Equation 53), the model sums them up to derive the resultant global irradiance ($I_{Glob,tilt}$; W/m^2).

$$I_{Glob,tilt} = I_{R,tilt} + I_{B,tilt} + I_{D,tilt}$$

Equation 58

$I_{Glob,tilt}$ represents the solar energy that is convertible to electric and thermal energy. Since the effective energy yield of PV/T collectors depends on the efficiency of the conversion, now the detailed calculation steps of this conversion mechanism will be presented.

First, the temperature-dependent electric efficiency (η_{elec}; dimensionless) is required to compute in the function of electric efficiency at the reference temperature ($\eta_{r,elec}$: dimensionless; Table 7), temperature coefficient for the solar system's electric efficiency (β_p: %/°C; Table 7), solar system's cell (surface) temperature (T_C; in °C) and ambient air temperature (T_a: °C; meteorological input from the MERRA-2 dataset).

$$\eta_{elec} = \eta_{r,elec} \cdot \left(1 - \beta_p \cdot (T_C - T_a)\right)$$

Equation 59

T_C is expressed by the air temperature (T_a), clearness index (K from the Equation 42) and nominal operating cell temperature (equal to 45°C under standard testing conditions; i.e., 800 W/m^2 of irradiance, 20°C of air temperature, 1 m/s of wind speed) (RETScreen, 2020).

$$T_c = T_a + \left(\frac{NOCT-20}{800} \cdot (219 + 832K)\right)$$

Equation 60

Each PV/T module has a maximum (nominal) power ($P_{max,EL}$: W; Table 7) that is highest under optimal weather conditions. Mostly, however, the power production is lower as compared to optimal value. As the Equation 61 suggests, the reduction is driven by the amount of radiation and the cell temperature of the PV/T collector. Consequently, the electric energy output generated on 1 m^2 of the solar system ($E_{EL\ output}$; W/m^2) can be given by:

$$E_{EL\ output} = \frac{I_{Glob,tilt}}{I_{Glob,STC}} \cdot \frac{\eta_{elec}}{\eta_r} \cdot P_{max,EL}$$

Equation 61

where $I_{Glob,STC}$ is the global irradiance on the tilted plane under standard testing conditions (1000 W/m^2).

Considering the miscellaneous and other losses of the PV/T collectors (L_{miscel}: dimensionless; Table 7), the electric energy production ($E_{EL\ prod}$; W/m^2) can be defined as:

$$E_{EL\ prod} = E_{EL\ output} \cdot (1 - L_{miscel})$$

Equation 62

$E_{EL\ prod}$ has to be further reduced to obtain the energy supplied to the power grid ($E_{EL\ supp}$; W/m^2).

$$E_{EL\ supp} = E_{EL\ prod} \cdot \eta_{inverter}$$

Equation 63

The Equation 63 means that $E_{EL\ supp}$ depends on the ability of the inverter to convert the generated direct current to altering current. In the BISE model, this efficiency is expressed by the following formula (Macêdo and Zilles, 2007):

$$\eta_{inv} = \frac{\rho_{DC} - (j_1 + j_2\rho_{DC} + j_3\rho_{DC}^2)}{\rho_{DC}}$$

where $\eta_{inverter}$ is the inverter's efficiency [dimensionless], $j_{1\text{-}3}$ are coefficients (j_1=0.0079, j_2=0.0411, j_3=0.0500) (Macêdo and Zilles, 2007) and ρ_{DC} is a conversion factor [dimensionless]. ρ_{DC} can be defined by:

$$\rho_{DC} = \eta_{elec} \cdot \frac{I_{Glob,tilt}}{I_{Glob,STC}} \ (28)$$

Equation 64

Finally, the technical potential of solar electric energy supply ($E_{EL\ total\ supp}$; in W) is estimated by distributing $E_{EL\ supp}$ according to $A_{PV/T\ syst}$ (the result of Equation 41) for each (r) region, (c) climate zone, (u) urban type, (b) building category, (t) building type and (v) building vintage.

$$E_{EL\ total\ supp_{r,c,u,b,t,v}} = E_{EL\ supp} \cdot A_{PV/T\ syst_{r,c,u,b,t,v}}$$

Equation 65

Turning to the presentation of the calculation steps for the solar thermal energy production, they follow the 1D interpretation of the Hottel-Whillier model in which the most important stages are to estimate the energy uptake and the occurring temperature change of the transfer fluid flows in the PV/T collectors. However, this 1D model is less detailed than the more complex 2-3D steady/dynamical models, it allows for the fastest calculation (Zondag et al., 2002), which is advantageous for global studies.

First, the inlet fluid temperature (T_{in}; °C), fixed at 20°C, is estimated by the thermal model. Then comes the outlet fluid temperature (T_{out}; °C) that is influenced by both the T_{in} and the thermal energy output generated by 1 m^2 of the PV/T collector ($E_{TH\ output}$; W/m^2).

$$T_{out} = T_{in} + \frac{1}{Mc_p} \cdot E_{TH\ output}$$

Equation 66

In the Equation 66, M is the mass of the water in the storage tank (M≈75 kg), c_p is the specific heat capacity of water (4186 J/kg °C). Similarly, the mean temperature of the flat plate collector (T_{pl}; °C) is also dependent on T_{in} and $E_{TH\ output}$:

$$T_{pl} = T_{in} + \frac{E_{TH\ output}(t-1)}{2mc_p} + \frac{E_{TH\ output}(t-1)}{A_c h_{co}}$$

Equation 67

where m is the flow rate of fluid (kg/s; Table 7), h_{co} is the heat transfer coefficient between the solar cell and the copper absorber (45 W/m^2 °C) and A_c is the normalized collector area (assumed to be 1 m^2 based on (Duffie and Beckman, 1982).

In this model, $E_{TH\ output}$ mutually depends T_{pl} (see Equation 68 and Equation 73), which implies that T_{pl} must be computed iteratively in the BISE model. To obtain $E_{TH\ output}$, first the conductive heat loss through the top of the PV/T collector (U_L; W/m^2 °C) is predicted.

$$U_L = \left\{ \frac{N \cdot T_{pl}}{C \cdot \left[\frac{(T_{pl}-T_a)}{N-f} \right]^e} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma \cdot (T_{pl}+T_a) \times (T_{pl}^2+T_a^2)}{(\varepsilon_p + 0.00591 h_w)^{-1} + \frac{[2N+f+0.133\varepsilon_p]}{\varepsilon_g} - N}$$

Equation 68

The unknown parameters in the Equation 68 are the following: N is the number of glass covers (equal to 1 following Duffie and Beckman, 1982), C is a latitude correction factor [in degrees], h_w is the wind heat transfer coefficient [m/s], f is a h_w-related correction factor [m/s], e is a T_{pl}-related correction factor [°C], ε_p is the emissivity of absorber plate [dimensionless; equal to 0.95 following Majid et al., 2015], ε_g is the emissivity of glass covers (considered to be 0.9 based on Pokorny and Matuška, 2020) and σ is the Stefan-Boltzmann constant [$5.67 \cdot 10^{-8}$ $W/m^2 K^4$]. C, h_w, f and e may be defined by:

$$C = 520(1 - 0.000051\varphi^2)$$

Equation 69

$$h_w = 2.8 + 3.0V_w$$

Equation 70

$$f = \left(1 + 0.089h_w - 0.1166h_w\varepsilon_p\right) \cdot (1 + 0.07866N)$$

Equation 71

$$e = 0.43\left(1 - \frac{100}{T_{pl}}\right)$$

Equation 72

where V_w is the wind speed [m/s] and φ is the latitude [degrees].

Now with the Equation 73, $E_{TH\ output}$ is finally given by the formula below:

$$E_{TH\ output} = F_R \cdot \left(I_{Glob,tilt} \cdot (\tau\alpha - \tau\eta_{elec}) - U_L \cdot (T_{in} - T_a)\right)$$

Equation 73

where F_R is the heat removal factor (estimated to be 0.85 based on Anderson et al., 2009), τ is the transmittance of the glass cover (equal to 0.9 based on Matuska et al., 2009), α is the shortwave absorptivity of the absorber (equal to 0.95 based on Majid et al., 2015), while $I_{Glob,tilt}$ and η_{elec} are the outputs of Equation 58 and Equation 59.

Considering the thermal losses from the storage tank (LTH; equal to 20% following Aisa and Iqbal, 2016), this estimation defines the thermal energy supplied by 1 m^2 of the PV/T system ($E_{TH\ supp}$; W/m^2).

$$E_{TH\ supp} = E_{TH\ output} \cdot (1 - L_{TH})$$

Equation 74

Finally, by multiplying $E_{TH\ supp}$ with the total area of the PV/T collectors $A_{PV/T\ syst}$ (the result of the Equation 41), the BISE calculates the technical potential of solar thermal energy supply ($E_{TH\_total\_supp}$; W) for a given (r) region, (c) climate zone, (u) urban type, (b) building category, (t) building type and (v) building vintage by the Equation 75.

$$E_{TH\ total\ supp_{r,c,u,b,t,v}} = E_{TH\ supp} \cdot A_{PV/T\ syst_{r,c,u,b,t,v}}$$

Equation 75

By simply summing the electric and thermal supply terms (the outputs of the Equation 65 and Equation 75), the total PV/T energy supply ($E_{PV/T\ total\ supp}$; W) is expressed with the following formula:

$$E_{PV/T\ total\ supp_{r,c,u,b,t,v}} = E_{EL\ total\ supp_{r,c,u,b,t,v}} + E_{TH\ total\ supp_{r,c,u,b,t,v}}$$

Equation 76

As it is seen, the BISE makes this aggregation on the appropriate (r) region, (c) climate zone, (u) urban type, (b) building category, (t) building type and (v) building vintage.

3.2.3. Description of modeling inputs

In this subsection, the input data that is used to solve the algorithms in the BISE model will be briefly introduced. These inputs form three groups to represent meteorological, technological and building-related parameters. First the building-related inputs are discussed.

The most important building-related in the BISE model is $A_{PV/T\ syst}$ that expresses the building rooftop area suitable for PV/T collector installation. Based on the Equation 37–Equation 41, to quantify this variable, there is a need to estimate parameters for the roof to floor ratio ($r_{roof\_to\_floor}$), floor area (FA) and utilization factor (U_F). The $r_{roof\_to\_floor}$ values, differentiated between regions, building types and subcategories (Table 5), were generated with detailed GIS classification on urban land cover and building height data (Petrichenko, 2014). Besides, FA is received from the HEB model and thus the desired input with the same disaggregation level can easily be achieved.

Table 5. Roof to floor ratios due to regions and building types used in the model (Petrichenko, 2014).

Region	**Residential**		**Commercial/Public**				
	Single family	**Multifamily**	**Educational**	**Hotels & restaurants**	**Hospitals**	**Retails**	**Offices**
AFR	0.90	0.36	0.57	0.73	0.51	0.92	0.25
CPA	0.63	0.11	0.14	0.23	0.16	0.33	0.08
EEU	0.49	0.15	0.22	0.30	0.21	0.43	0.10
FSU	0.51	0.20	0.30	0.39	0.28	0.57	0.14
LAC	0.78	0.37	0.55	0.74	0.52	0.92	0.26
MEA	0.56	0.18	0.28	0.37	0.26	0.53	0.13
NAM	0.62	0.13	0.20	0.27	0.19	0.39	0.09
PAO	0.63	0.30	0.45	0.60	0.42	0.87	0.21
PAS	0.70	0.44	0.66	0.89	0.62	0.92	0.31
SAS	0.85	0.32	0.48	0.64	0.44	0.92	0.22
WEU	0.40	0.21	0.32	0.42	0.30	0.62	0.15

Discussing U_F more in detail, this variable is known to have 9 components and applied as a reduction factor to the total roof area. As a very crucial factor of U_F, the roof tilt coefficient (C_{SL}) gives the rooftop area decrease due to the angle of the roof. The estimation of C_{SL} relies on the angular distribution of the building roofs. Without having detailed global information on this aspect, literature data was employed to fill this gap. For commercial/public building types, 100% of the rooftops were assumed to be flat (C_{SL} =1). For residential buildings, a typical share of 75% and 25% was concluded in several publications (e.g., Margolis et al., 2017; Wiginton et al., 2010). Although aware of that the roof tilt varies by regions and climate, the data scarcity made necessary to apply this share identically for the residential rooftops of different regions.

Note that the tilt angle was given by Equation 45. By considering $\beta_{NORTH}/\beta_{SOUTH}$ as tilt angles, it was hypothesized that each residential rooftop enables the optimal utilization due to its tilt angle. As a result of inter-regional and inter-annual differences of β_x (multiple φ values within a region) and solar parameters (various radiation potential during the year), C_{SL} is predicted to be lower than 1 (scatters around 0.7).

On flat rooftops, PV/T collectors are typically installed with a certain tilt (the same β values were used on regional basis), which results in restricted sky view and shading, without having adequate set-back (i.e., panel separation) between the collectors. The rooftop area reduction due to this set-back is expressed via C_{GR} and is calculated by:

$$C_{GCR} = \frac{1}{cos\beta_{NORTH/SOUTH} + SBR \cdot sin\beta_{NORTH/SOUTH}}$$

Equation 77

where $\beta_{NORTH}/\beta_{SOUTH}$ is the output of the Equation 45 and SBR is the set-back ratio (equal to 3 following Romero Rodríguez et al., 2017). Rooftop reductions due to service and construction area, protected buildings, orientation and shading are considered with the coefficients listed in the Table 6.

Table 6. Estimated values of U_F coefficients separated by flat and pitched roofs.

Applied coefficients	Flat roofs	Pitched roofs	Reference
C_{CON}	0.8	0.9	Byrne et al. (2015)
C_{PROT}	1	1	–
C_{SH}	0.7	0.8	Kurdgelashvili et al. (2016); Romero Rodríguez et al. (2017)
C_{SA}	0.97	1	Byrne et al. (2015)
C_{AZ}	1	0.5	Wiginton et al. (2010)
C_{SL}	1	Eqs. 8 and 21.	–
C_{GCR}	Eq. 46.	1	Romero Rodríguez et al. (2017)
C_{PV}	1	1	–
C_{ST}	1	1	–

As pointed out earlier, U_F is applied for the total roof area (RA_{total}) to estimate the fraction of the rooftop available for PV/T collector installation. RA_{total}, as the Equation 37 suggests, plays an important role in determining the spatiotemporal evolution of the building rooftop area. Precisely, the model employs geospatial data to derive the spatial distribution of rooftops for the initial year of the simulation period ($RA_{total\ 2022}$) and uses floor area tendencies along with roof to floor ratio to generate the dynamic of the RA_{total}. The estimation of $RA_{total\ 2022}$ in the BISE follows the methodology proposed by Bódis et al. (2019).

The current method for computing $RA_{total\ 2022}$ is based on the supervised classification of the global and open-source dataset of Human Settlement Layer (HSL) that has been produced and supported by the Joint Research Centre (JRC) and the DG for Regional and Urban Policy (DG REGIO) of the European Commission. This dataset consists of high-resolution (10-m) and geo-referenced (UTM coordinate system) geotiff files that were originally derived from Sentinel-2 satellite images (Corbane et al., 2021). These raster layers display the probability of the occurrence of build-up surfaces (P; %) in a given 100 m^2 pixel.

In out methodology, it was assumed that the higher the P the more probable that a given pixel represents a building footprint. In order to find this probability threshold, building cadastral maps were employed from four countries (Czech Republic, France, Belgium and Spain) and more than 50 urban areas. After reprojecting the data accessed at the INSPRINE Geoportal (INSPIRE, 2020) to the projection of HSL images, zonal statistics of the P values were computed using the QGIS freeware geospatial software. The statistical analysis indicated that the P=60% can be considered as a lower limit in the classification.

Then the whole classification process was automatized by Python scripts wherewith a high granularity map of the building footprints was generated. By combining the shapefiles of the BISE' regions with this map (Figure 21) and by considering the building footprint area being equal to the rooftop area, the raw values of the rooftop areas in each region were determined. In other words, as the Equation 38 implies, the best achievable disaggregation for $RA_{total\ 2022}$ is at regional level. By taking the share of building types and roof tilt as well as the ideal β angles into account, the initial $RA_{total\ 2022}$ values (i.e., the ones computed in the above manner) were upscaled (i.e., $area_{flat} < area_{slanted}$) using elementary trigonometry to harmonize the estimated $RA_{total\ 2022}$ and U_F inputs.

Figure 21. Subset of HSL data overlaid by building cadaster (Granada, Spain).

The next type of inputs represents the meteorological variables for temperature (T_a; e.g., in the Equation 73), wind speed (V_W; e.g., in the Equation 70), surface global radiation ($I_{Glob,h}$; e.g., in the Equation 43) and top of atmosphere incoming shortwave radiation (I_{TOA}; e.g., in the Equation 42). The meteorological parameters are retrieved from the NASA's Goddard Earth Sciences (GES) Data Information Services Centre (DISC) MERRA-2 (Modern-Era Retrospective analysis for Research and Applications) reanalysis dataset (Gelaro et al., 2017). The selected gridded (raster) dataset covers a 5-year period (between 2015 and 2019) and has hourly temporal resolution. Based on the representative values at the same time step and grid point, mean annual profiles were created for each variable. Then the mean hourly, pixelwise values were converted into profiles for mean hourly weights (c; dimensionless) for each parameters in each time step (i – month, j – day, k – hour). The procedure of calculating the c for the V_w was done as follows:

$$c_{ijk} = \frac{V_{w,ijk}}{V_{w,mean,ijk}}$$

Equation 78

where $V_{w,mean,ijk}$ is a normalization factor that represents the pixelwise mean of V_W in a given (i) month, on a given (j) day and at a given (k) hour. By definition, c scatters around 1, depending on periods with positive or negative anomaly (Figure 22).

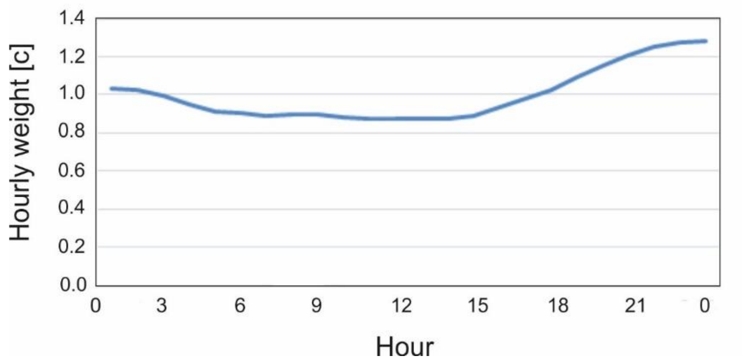


Figure 22. Hourly weights [in UTC] of computed for the wind speed on January 1st 2022 in the grid point (55, 55).

In the next step, climate data is used to represent the spatiotemporal variation of the meteorological variables over the modeling period. For our model, this data was accessed from the CMIP6 (Climate Model Intercomparison Project) dataset and the outputs were granted by the modeling experiment of the DKRZ (German Climate Computational Centre) model (Schupfner et al., 2019). These climate projections were forced by the SSP 1-2.6 scenario (see further in Riahi et al., 2017), which means that a future climate with strongly declining greenhouse gas emission was considered in the BISE. Given that this (and most) projection(s) is (are) only available with daily temporal resolution, the climate data is needed to be refined in time, in our methodology, employing the mean hourly weights.

Before the temporal refining process, the output netCDF files with the c values were regridded with bilinear interpolation method by using a CDO (climate data operator; Schulzweida, 2019) bash script to achieve a match between the resolutions of the MERRA-2 (≈50-km horizontal resolution) and DKRZ (≈100-km horizontal resolution) data. Then to refine the climate projections, the following equation was solved for each meteorological variable (now this step is shown for T_a):

$$T_{ijk} = c_{ijk} \cdot T^*_{ij}$$

Equation 79

where T^*_{ij} is the mean daily air temperature in a given (i) month and on a given (j) day from the DKRZ data, c_{ijk} is the output of the Equation 78 for the air temperature in a given (i) month, on a given (j) day and at a given (k) hour from the MERRA-2 data, while T_{ijk} is the refined hourly air temperature from the DKRZ data. Note that same c profiles were applied to the DKRZ data in each year of the BISE's modeling period. After this procedure, the modified climate dataset contains 384*192*8760 (longitudinal grids*latitudinal grids*time steps) value for each variable and in each year (Figure 23).

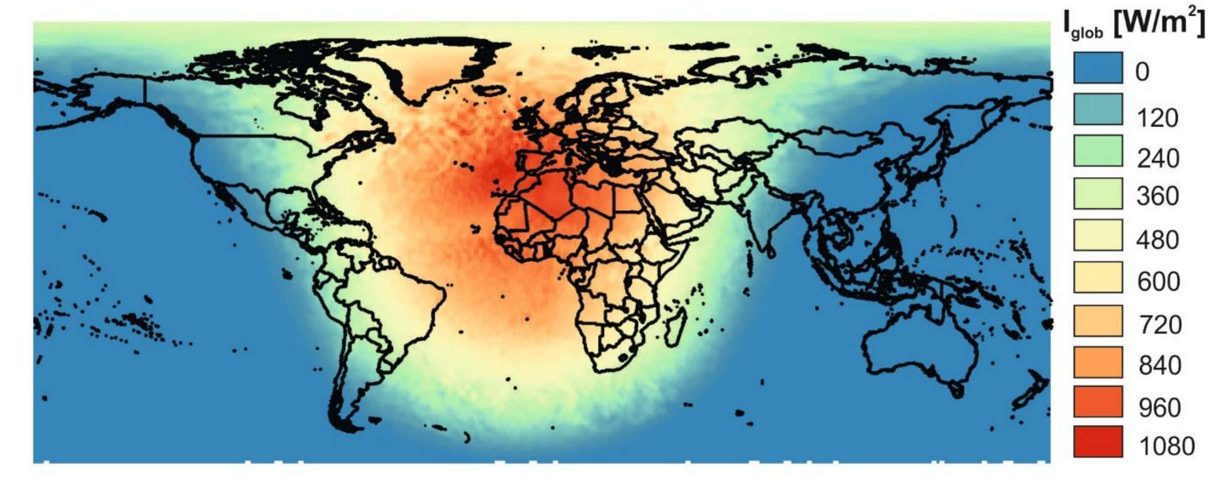


Figure 23. Global distribution of derived global radiation input on July 1st 2022.

To discuss the third main group of inputs, the selected technological parameters intend to express the characteristics of the state-of-the-art PV/T technologies in the BISE model. For deriving these inputs, the product specifications of more than 20 hybrid PV/T collectors were reviewed. The purpose of the review was to assess the typical ranges of values in terms of such relevant technological measures as the nominal thermal (η_{TH}) and electric efficiency ($\eta_{r,elec}$), temperature dependency of electric efficiency (β_p), nominal electric ($P_{max,EL}$) and thermal output ($P_{max,TH}$), inverter efficiency and typical flow rate (m). Figure 24 depicts the $\eta_{r,elec}$ and η_{TH} values as per the reviewed collectors. As being illustrated, owe to the ongoing development of the solar technology, the $\eta_{r,elec}$ and η_{TH} of the most improved PV/T modules exceeds the 20% and 70% recently.

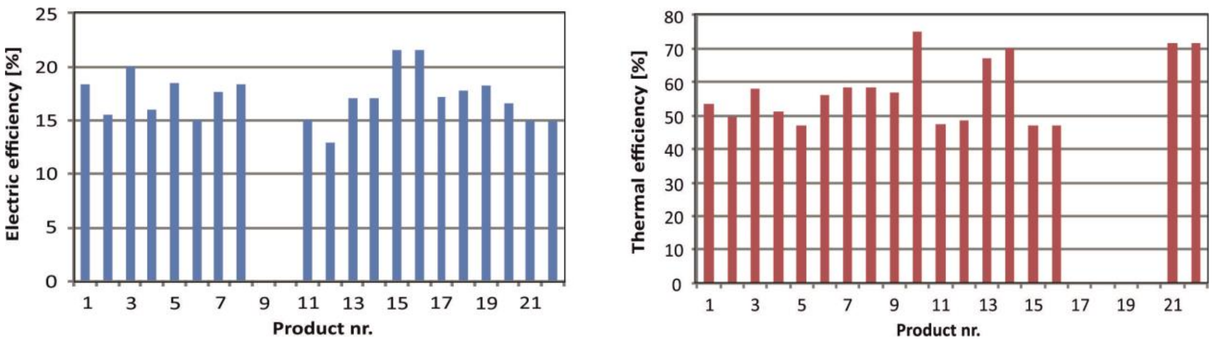


Figure 24. Electric and thermal efficiencies of the reviewed PV/T collector products.

For β_p, it was found that there are only small differences (≈0.05%/°C) in the response of the electric efficiency to the surface temperature change of the silicon cells of the PV/T modules. Precisely, the β_p values of the reviewed products varies generally between –0.33%/°C and –0.50%/°C (Figure 25). Slightly larger deviations were concluded for the $P_{max,EL}$ (270–375 W_p) and $P_{max,TH}$ (600–750 W_p), which reflects to the great diversity of efficiency values, depending on the applied technology.

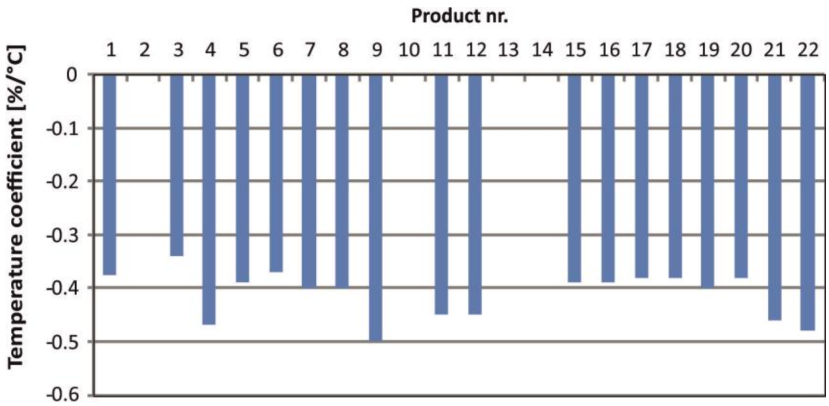


Figure 25. Reviewed values of the PV/T collector's temperature coefficient.

Since the main purpose of the BISE is to estimate the highest solar energy production technically (incl. technologically) possible on building rooftops with PV/T collectors, the technological measures from the above ranges were chosen to guarantee this consideration. The finalized parameters are summarized in the Table 7. Additionally, two constraints were imposed during the modeling activity because of data lacking, which included the neglect of the degradation and the technological progress of the PV/T modules over the 39-year analysis period. Nevertheless, these simplification may offset themselves, therefore the modeling uncertainty could be held at a reasonably low level.

Table 7. Technical specification of hypothesized PV and PV/T modules used during the modeling activity.

PV panel	Variable	PV/T collector
monocrystalline Si	Technology	monocrystalline Si
23% (SUNPOWER, 2021)	η_r – Nominal electric efficiency	21.6% (TRIPLE SOLAR, 2021)
–0.27%/°C (SUNPOWER, 2021)	β_p – Nominal temperature coefficient	–0.34%/°C (DUALSUN, 2021)
400 W (SUNPOWER, 2021)	P_{max} – Nominal power	375 W (DUALSUN, 2021)
20%	L_{miscel} – Miscellaneous losses	20%
–	m – Flow rate of fluid	0.027 (TRIPLE SOLAR, 2021)

However, the BISE model has been tailored for estimating the solar energy production by PV/T collectors, the flexibility of the modeling framework makes it possible to assess the energy supply by arbitrary solar systems. For this reason, the model was completed with a module that aims to simulate the technical potential of PV power generation. The calculation of the electric energy output by rooftop PV panels follows the Equation 37–Equation 65, but considers different inputs for the technological parameters. The PV-related inputs represent the performance numbers of a specific PV product (SunPower Maxeon 3). This prototype is designed with IBC (Interdigitated Back Contact) cell technology and with its reference electric efficiency of 23% (Table 7), the Maxeon 3 panels are among the most efficient residential PV modules currently. In this regards, the capability of the BISE model in providing and comparing simulations with two solar technologies enable to explore the potential benefits and drawbacks of mass rooftop PV/T collector and PV panel installation. However, examining the financial return period of applying these technologies is out of the scope of this report.

3.2.4. Scenario description

The scenario in BISE model were created to assess the influence of an “expected” penetration pathway of rooftop PV/T and PV modules on the technical potential of on-site solar energy production. In this scenario, the degree of the penetration is characterized by the level (i.e., what fraction of the building rooftops is covered by PV/T or PV modules) and the dynamic (i.e., how fast the installation of PV/T or PV modules will occur) of the utilization. The penetration rate of the rooftop solar panels was constructed by extrapolating the historical changes in the PV production for the modelling period. As a result a “quasi-exponential curve” was anticipated for the next decades shown in Figure 26. As an initial value for utilization, we selected the 10% of the available roof areas, irrespectively to region, given that around 90% of the physically suitable rooftops are considered to be ready for being covered by solar panels (SolarPower Europe, 2019). Furthermore, it was prescribed in the scenario that after installing physically suitable areas, the intermittently or permanently unfavorable roof spaces (for example, due to shading or orientation) are also used for solar energy conversion purposes. Naturally, the installation was maximized when no free roof area remained.

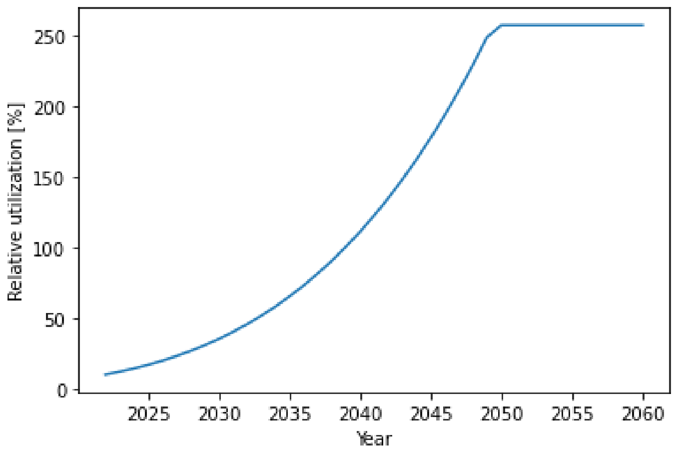


Figure 26. The relative change of the utilization factor in the BISE’s scenario. The relative utilization expresses the PV or PV/T coverage on building rooftops relative to the suitable rooftop area.

4. Results and discussion

4.1. The potential of energy demand reduction

The findings of this report are presented in three sub-categories to show the energy demand reduction potential of space heating, cooling and hot water along with its associated CO_2 emissions. As it is discussed in sections 3.12 and 3.13, both space heating and cooling largely depends on the floor area growth, and hence first, we present the global floor area projections across different scenarios, then we present the annual energy demand for space heating and cooling across different scenarios and climate zones. Along with the annual energy demand data, it is important to analyze the hourly demand profile, as energy demand varies in different season and in different climate zones. Furthermore, without understanding the hourly demand profiles, we will not be able to check the building self-sufficiency principals. Thus, this study also presents the hourly demand profiles for each of the regions, and focus countries separately.

Final energy use for space heating and cooling in three different scenarios clearly shows the immense potential to reduce energy demand of the building sector by 2060. At the global level, if best practices can be implemented then final energy for heating and cooling demand would be halved by 2060. On the other hand, remarkable increases can be concluded if the current trends persist. Regions like the USA or EU27 show a much higher potential to reduce space heating and cooling related energy use with the help of the best practices. The heating and cooling energy consumption of buildings can practically reach zero in the EU, USA and Pacific OECD countries by 2055-2057. In the meantime, China and India would not reach to zero over the modelled period. Globally the commercial and public buildings in the urban area are the largest consumer of space heating and cooling-related energy.

Globally similar to energy use for thermal comfort, energy use for hot water can also be reduced significantly (by around one third) in the Deep Efficiency scenario. This reduction may be the highest in the residential sector. The Net Zero scenario shows similar trends as for heating and cooling energy demand, meaning that the demand can be lowered remarkably in the EU, USA and Pacific OECD by applying on-site solar energy supply.

Being in line with the energy demand predictions, significant CO_2 emission reduction could be achieved by introducing more efficient buildings into the stock. In the "Deep scenario", the global CO_2 emission was estimated to reduce mostly for the space heating and hot water production. For the space cooling, no major emission reduction could be obtained due to the increasing demand with the climate change. As per the results, the building sector could not entirely reach neutrality in the emission by 2060 in none of the analyzed regions. However, significant efforts could be made based on the selected energy efficiency pathway.

4.1.1. The future dynamics of global floor space

To calculate the final energy demand and floor area, first population is disaggregated into urban and rural, climate zones, and building categories by using Equation 1Equation 6. Similarly, the GDP is disaggregated as per different climate zones, and urbanization rates by using Equation 7Equation 9 as HEB model assumes that the residential sector floor area growth mostly depends on population growth, while the non-residential or commercial floor area growth depends on the GDP growth of a region. Once the input data is disaggregated as per urbanization rate, building categories and climate zones, the floor area for each of the regions is calculated by using Equation 10 and Equation 11. Based on these equations and assumptions, the findings from the HEB model show that the global floor area grows by 77% from 2022 to 2060, and the global floor area growth is mostly dominated by the floor area growth in the Asian and Middle East African regions. Precisely, substantial growth in floor area can be observed in the Middle East and Africa (180%), followed by Pacific Asia (174%), Africa (131%), and Latin America (130%) (refer to Figure 27Figure 33). The key reasons behind the substantial growth in floor area are increasing population growth, and GDP floor space per capita. Additionally, it can be observed that the substantial increase in the floor area is dominated by urban floor area, which is mostly caused due to an increasing rate of urbanization.

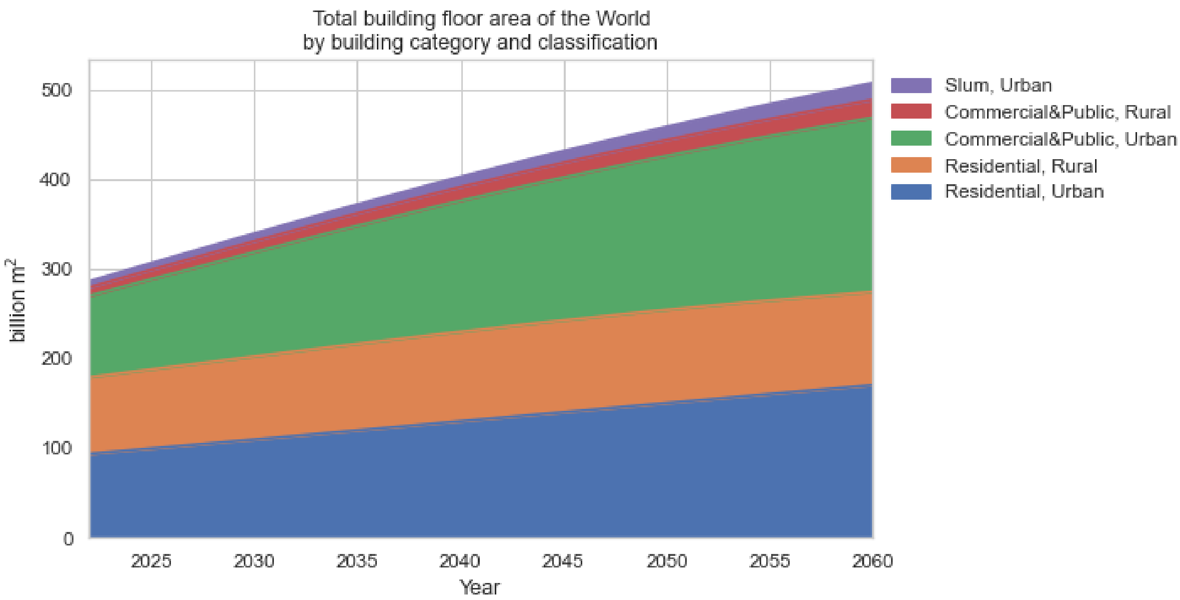


Figure 27. Change in total floor area with respect to urban / rural context as well as building category

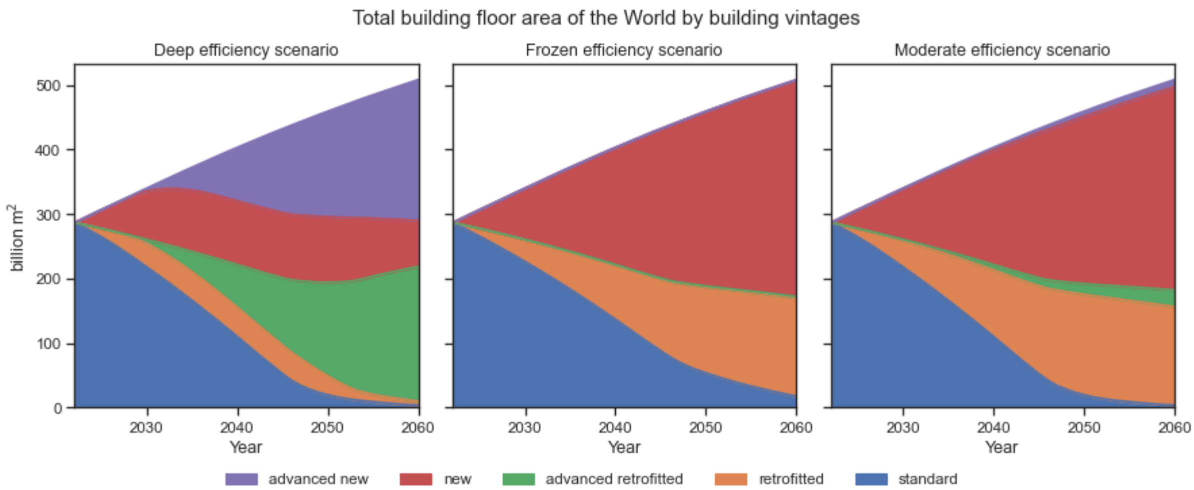


Figure 28. Distribution of World total floor area by building vintages across the modelling period.

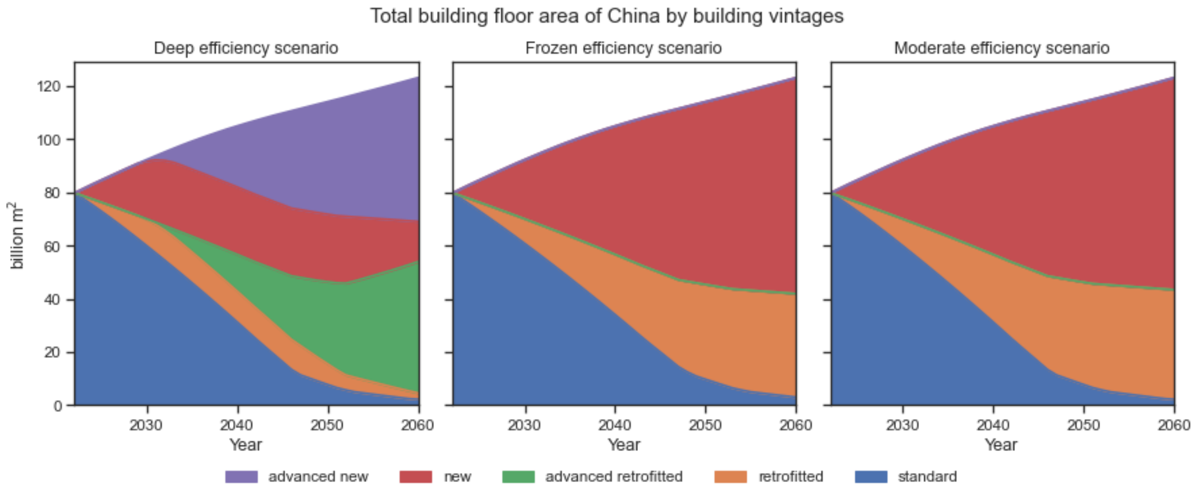


Figure 29. Distribution of total floor area in China by building vintages across the modelling period.

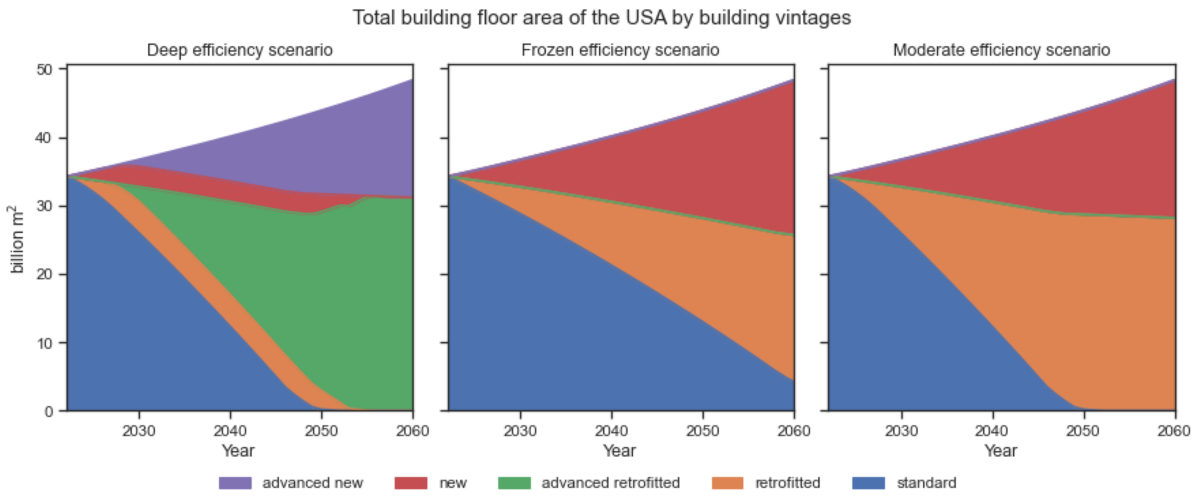


Figure 30. Distribution of total floor area in the USA by building vintages across the modelling period.

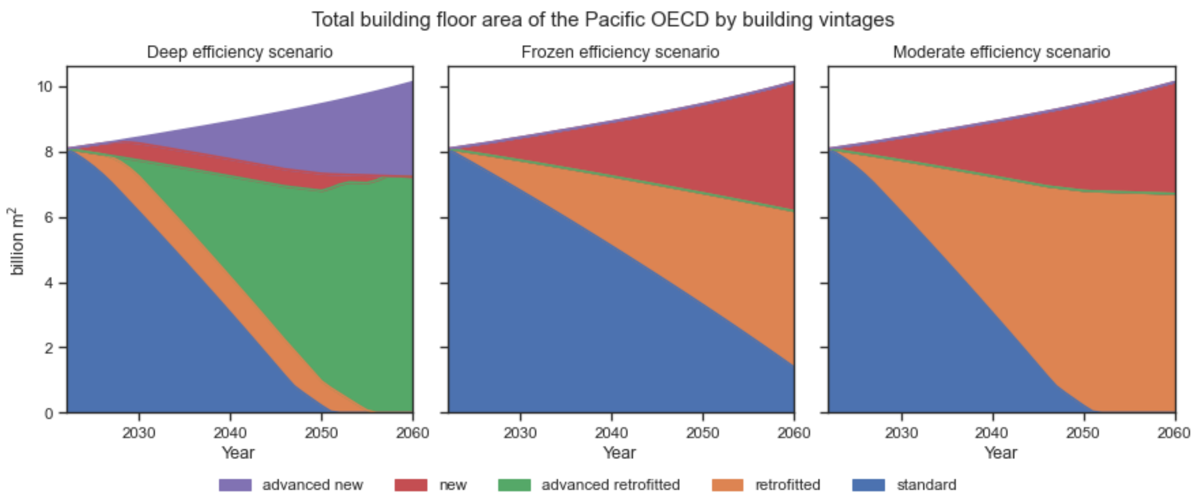


Figure 31. Distribution of total floor area in the Pacific OECD by building vintages across the modelling period.

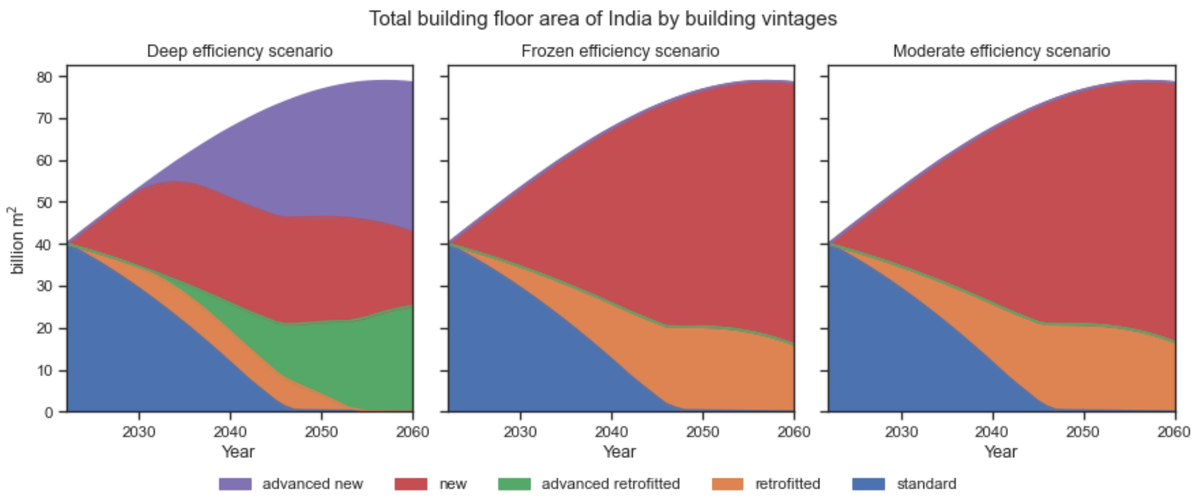


Figure 32. Distribution of total floor area in India by building vintages across the modelling period.

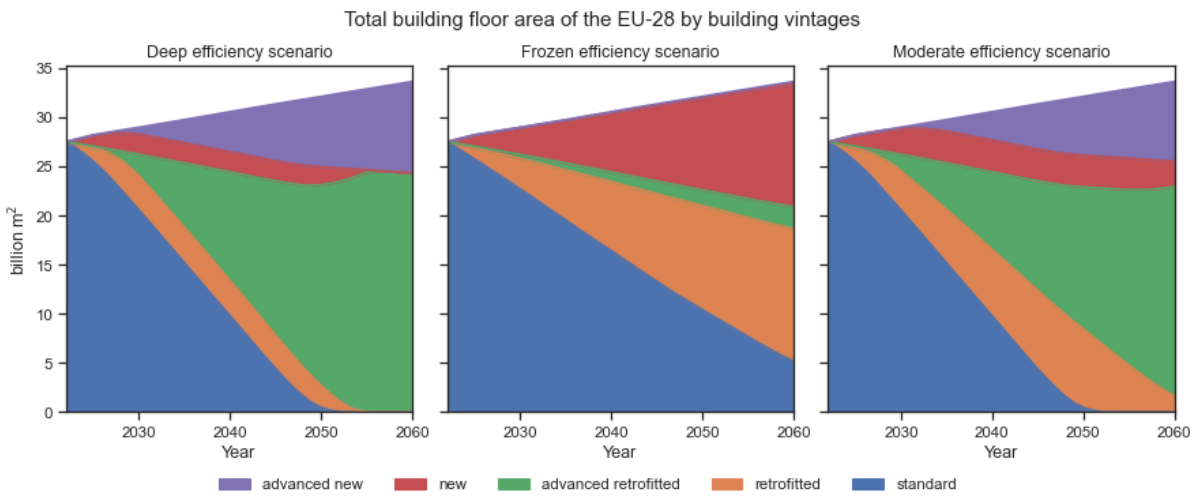


Figure 33. Distribution of total floor area in the EU by building vintages across the modelling period.

From Figure 27 to Figure 33, we can see that although, total floor area remains same across scenarios, the share of building vintages changes. This is mostly because of HEB assumptions of different building vintages in different scenarios. Furthermore, regions such as the Middle East and Africa, Africa, and Pacific Asia projects significant population and GDP growth in the future, and hence, floor area growth in these regions is substantial. If the global growth in floor area is further analyzed as per different building categories and classification, it can be observed that a substantial increase in the floor area is dominated by urban floor area (100% growth is projected by 2060 compared to 2022), which is mostly due to an increasing rate of urbanization. Urban slums are expected to rise dramatically to 176% by 2060 as a result of increased urbanization. However, slums do not represent a large percentage of global floor space (2.4 percent of global floor area belongs to slums, which is expected to rise to 3.7 percent), hence slum growth has little impact on global floor area growth.

Furthermore, if floor area growth is studied according to building classification, significant expansion can be predicted for the residential building sector, with commercial floor space expected to grow significantly as well. More specifically, the global residential construction sector is expected to rise from 179 billion m2 in 2022 to 275 billion m2 in 2060 (a 53% increase), while the global commercial building sector is expected to grow from 100 billion m2 in 2022 to 214 billion m2 in 2060. (114% increase). China's and India's total floor area expansion is mostly responsible for the increase in total floor area. For example, China's part of worldwide total floor area by 2060 will be around 24%, while India's share will be 15% by 2060.

If all new and refurbished buildings follow today's best energy efficiency practices ("Deep efficiency" scenario), more than two third of stock will be advanced new and advanced retrofitted in 2060 globally. The conclusions of this analysis also show that just a small portion of today's building stock will remain unchanged until 2060, implying that the majority of the building stock will need to be renovated or demolished, necessitating the construction of new structures.

Because all scenarios have the same total floor area, the most essential component of the scenarios is the share of vintage types and how it changes through time. One of the model's principal messages is that just a small portion of today's building stock will remain unchanged until 2060. As a result, it's critical to keep track of how many retrofitted and new buildings are outfitted with advanced efficiency features. In 2060, 43% of the building stock can be categorized as advanced new and 41% of the building stock can be classified as advanced retrofitted if today's best energy efficiency measures are applied to all new and retrofitted structures ("Deep efficiency" scenario). On the other hand, if existing practice is "frozen" and no advanced measures are implemented, 99% of the stock would remain inefficient in 2022, while the rest will remain unchanged. It's worth noting that, according to our forecast, 66% of the building stock in 2022 won't be ready until 2060. The "Moderate efficiency" scenario assumes that only current policy actions are implemented, and that no new, more ambitious goals are set for the world. Only 4% of the total floor area will be classified as "advanced" in this scenario (1% as new and 3% as retrofitted). This can be explained by the fact that countries with strong policies for energy efficient buildings have a competitive advantage (especially the EU) play minor role in the share of new buildings around the globe.

4.1.2 Estimating final annual energy demand

After calculating the floor area, final energy demand for different end-uses is calculated by using Equation 12, HEB model calculates energy demand for space heating, cooling, and hot water and thus, the total energy demand of the building sector only reflects summation of these three ends uses. Similar to the floor space calculations, the thermal energy demand and demand for hot water is also calculated for four scenarios.

The enormous potential to reduce energy demand in the building industry by 2060 is clearly demonstrated by the final energy usage for space heating and cooling in three different scenarios. If best practices are applied at globally, final energy for heating and cooling demand might drop to 5 PWh in 2060 from 22 PWh in 2022, a 78% reduction (refer to Table 8 and Figure 34). However, assuming current policies are maintained through 2060, total energy consumption will increase by 36% by 2060 compared to 2022 levels. In other words, compared to 2022, the global final energy for space heating and cooling increases by 36% in the Moderate Efficiency scenario until 2060. Global final energy in 2060 is 70% lower in the Deep Efficiency scenario than in the Moderate Efficiency scenario, but it is 31% greater in the Frozen Efficiency scenario, corresponding to an 79% rise above 2022 levels. One possible explanation for this trend is that the Frozen Efficiency scenario has lower retrofit rates than the Moderate Efficiency scenario, and that the share of advanced buildings is kept at a very low level in this scenario, even in regions where existing policies would require an increased share of advanced buildings (e. g. EU27). This emphasizes the importance of policies that are already in place.

Because key regions such as China, the EU27, and India consume the majority of global energy, it is critical to examine how the building sector in these areas might do under various scenarios (Figure 37). With the support of best practices, regions such as the United States and the EU27 have a substantially larger potential to minimize space heating and cooling-related energy use. If best practices are followed, energy consumption linked to thermal comfort in the United States and the EU27 can be lowered by 73% and 75%, respectively, by 2060. The Net Zero scenario takes the Deep Efficiency scenario a step further. The results reveal that by 2055-2057, building heating and cooling energy use in the EU, US, and Pacific OECD countries will be close to zero (Figure 37). Even though heating and cooling-related energy consumption in China and India will not approach zero in the projected timeframe, there will be a large reduction (68% in China and 24% in India) in comparison to 2022 estimates.

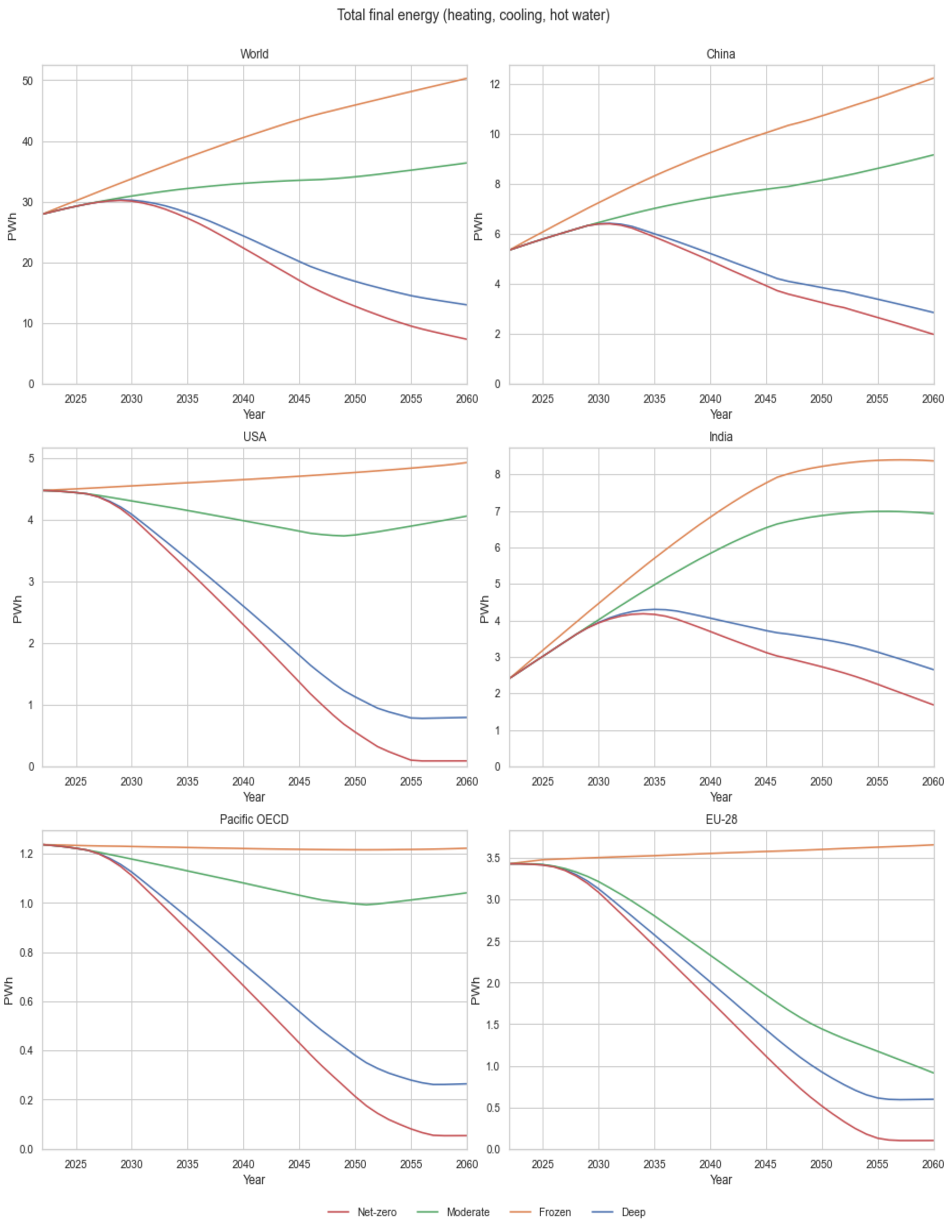


Figure 34. Total final energy consumption in the World and in key regions (in PWh).

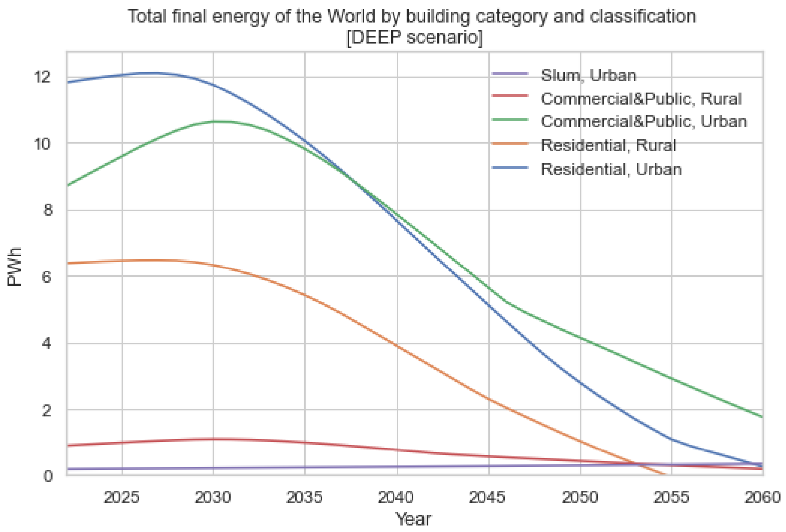


Figure 35. Total final energy consumption in the World by building category and classification (in PWh).

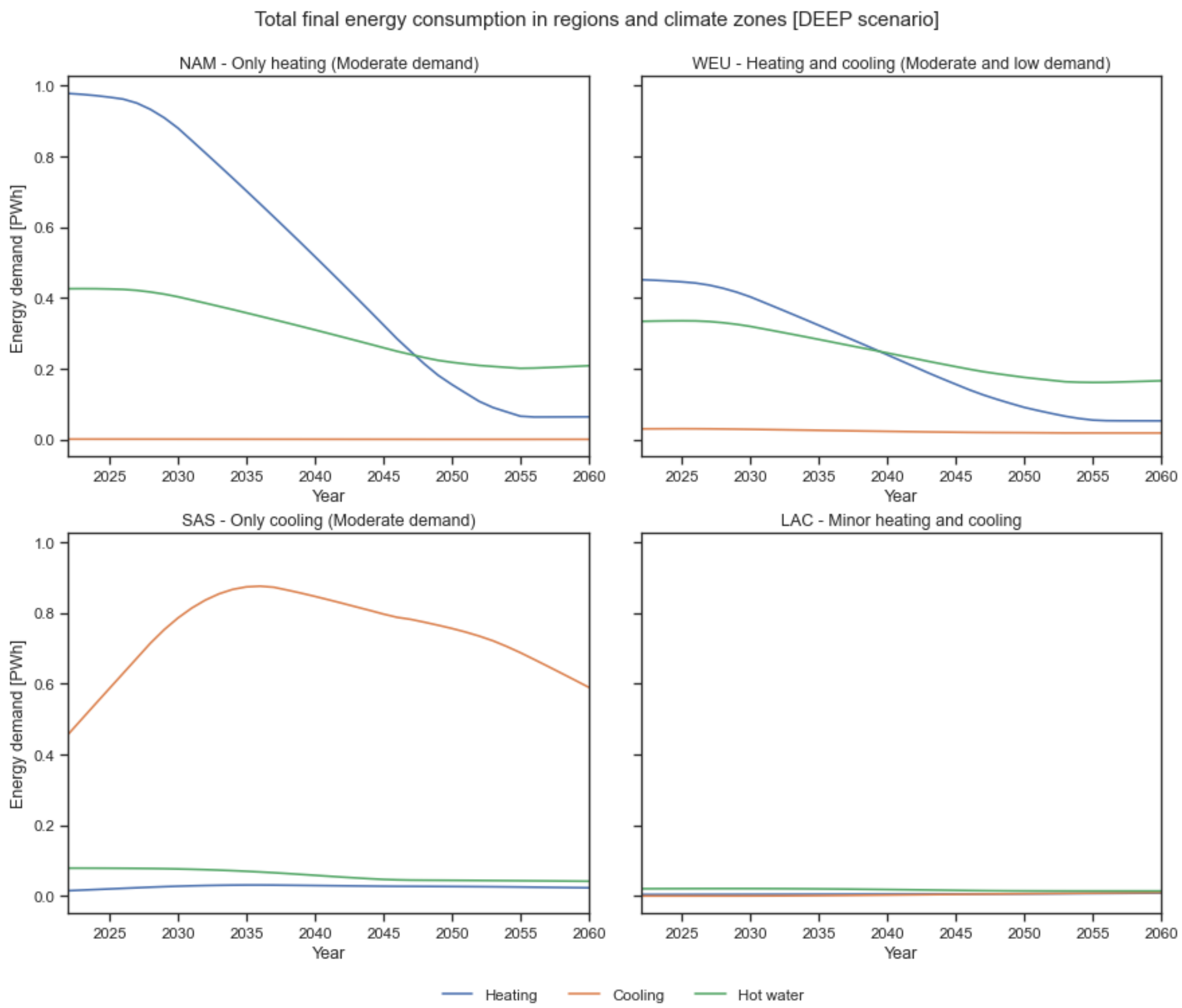


Figure 36. Final energy consumption for space heating, cooling and hot water production in given regions and climate zones predicted by the DEEP scenario (in PWh).

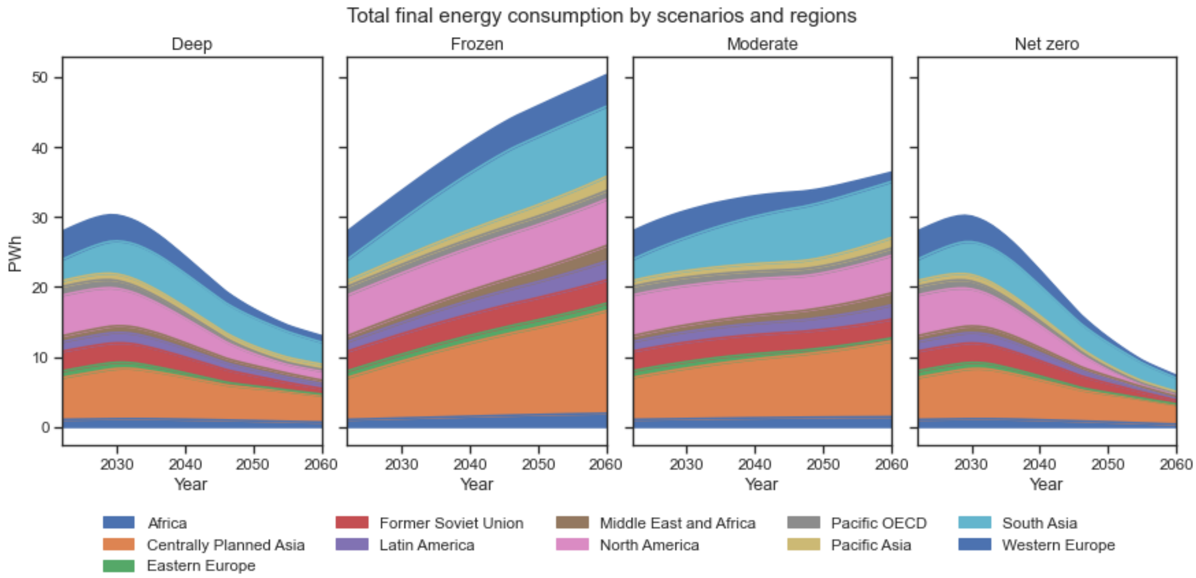


Figure 37. Share of regions within the total heating and cooling energy consumption of the World.

Table 8. Results for total final energy use in the key regions and the World.

Scenario	Baseline	Moderate Efficiency		Deep Efficiency			Net Zero			Frozen		
	2022 PWh	**2060 PWh**	**Δ% to 2022**	**2060 PWh**	**Δ% to 2022**	**Δ% to Moder.**	**2060 PWh**	**Δ% to 2022**	**Δ% to Moder.**	**2060 PWh**	**Δ% to 2022**	**Δ% to Moder.**
China	5.35	9.16	+71%	2.86	-47%	-69%	1.98	-63%	-78%	12.23	+129%	+34%
EU-28	3.43	0.55	-73%	0.60	-83%	-35%	0.01	-96%	-89%	3.66	+7%	+301%
India	2.40	6.92	+188%	2.65	+10%	-62%	1.68	-30%	-76%	8.37	+248%	+21%
Pacific OECD	1.24	1.04	-16%	0.26	-79%	-74%	0.05	-96%	-95%	1.22	–1%	+17%
USA	4.48	4.06	-9%	0.79	-82%	-80%	0.09	-98%	-98%	4.93	+10%	+21%
World	27.96	36.39	+30%	13.02	-53%	-64%	7.35	-74%	-80%	50.32	+80%	+38%

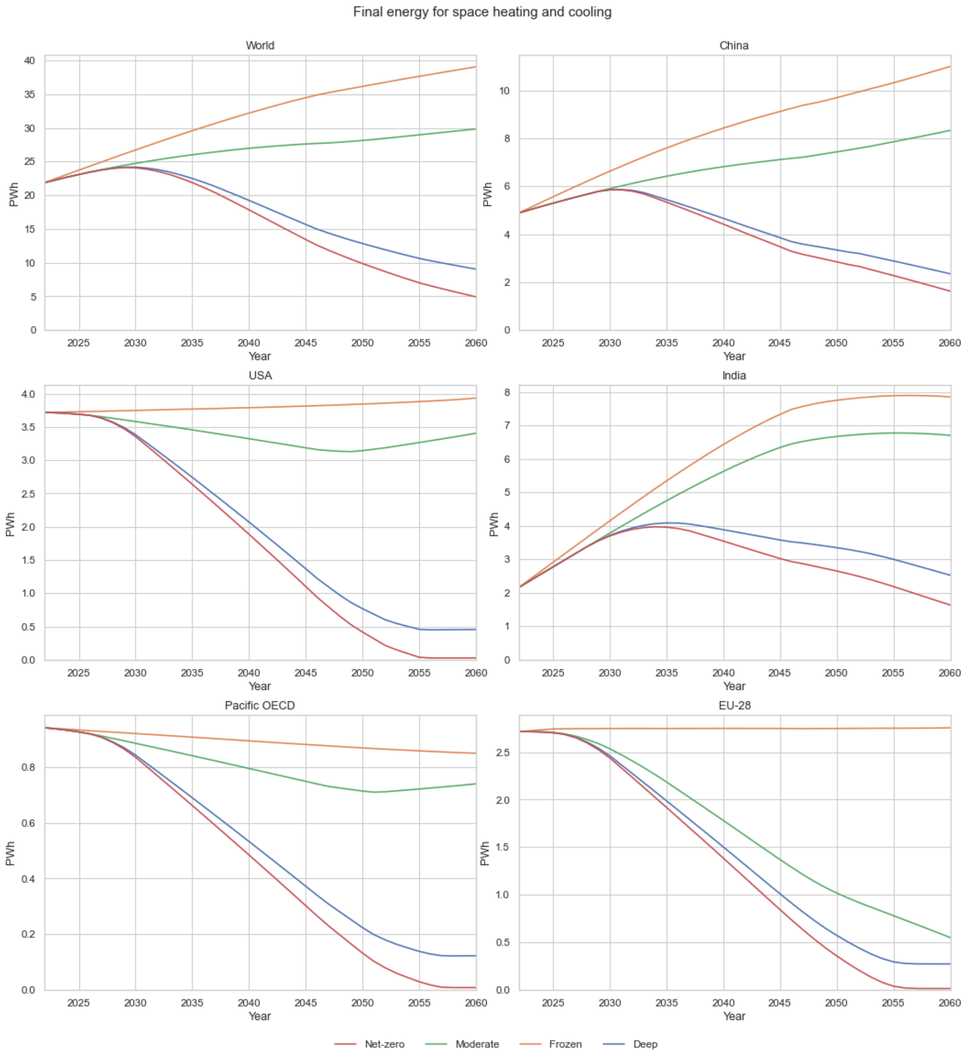


Figure 38. Final energy for space heating and cooling in focus countries and the World according to the scenarios.

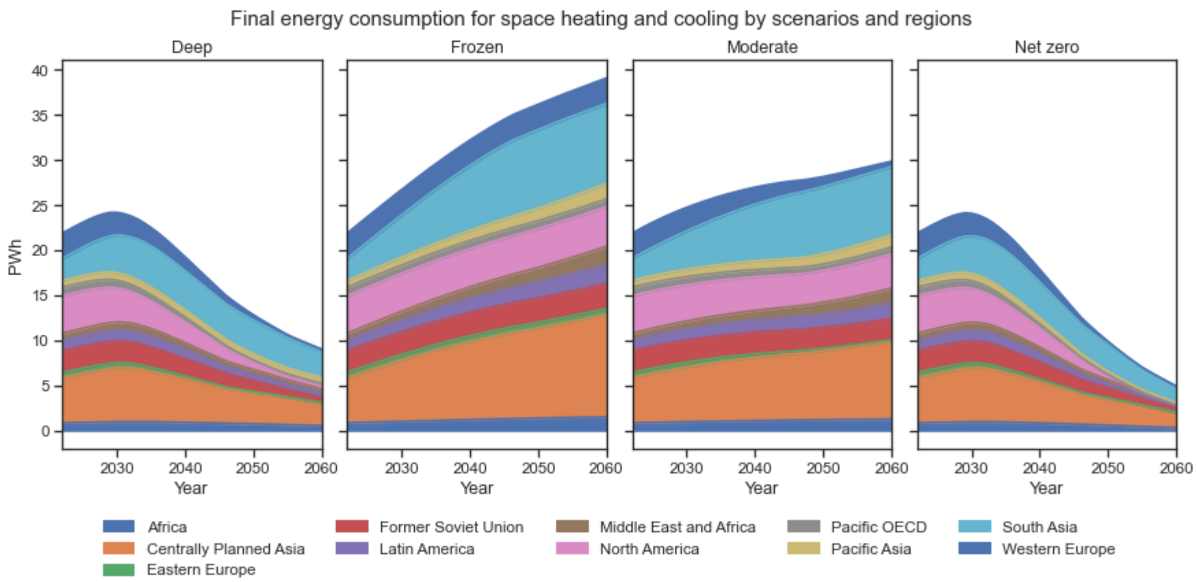


Figure 39. Share of regions within the total heating and cooling energy consumption of the World.

Table 9. Results for final energy use for heating and cooling in the key regions and the World.

Scenario	Baseline	Moderate Efficiency		Deep Efficiency			Net Zero			Frozen		
	2022 PWh	**2060 PWh**	**Δ% to 2022**	**2060 PWh**	**Δ% to 2022**	**Δ% to Moder.**	**2060 PWh**	**Δ% to 2022**	**Δ% to Moder.**	**2060 PWh**	**Δ% to 2022**	**Δ% to Moder.**
China	4.89	8.33	+70%	2.34	-52%	-72%	1.62	-68%	-81%	11.00	+125%	+32%
EU-28	2.72	0.55	-80%	0.27	-90%	-51%	0.01	-100%	-98%	2.76	+1%	+403%
India	2.16	6.70	+210%	2.52	+17%	-62%	1.64	-24%	-76%	7.85	+263%	+17%
Pacific OECD	0.94	0.74	-21%	0.12	-87%	-84%	0.01	-99%	-99%	0.85	–10%	+15%
USA	3.72	3.41	-8%	0.46	-88%	-87%	0.03	-99%	-99%	3.94	+6%	+16%
World	21.88	29.83	+36%	9.03	-59%	-70%	4.92	-78%	-84%	39.07	+79%	+31%

Commercial and public buildings in urban areas utilize the most space heating and cooling-related energy globally. As a result, best practices in the urban region should concentrate on commercial and public structures. In the Deep Efficiency scenario, commercial and public buildings in the urban region can lower their energy use by up to 80% by 2060. Similarly, in the Deep Efficiency scenario, worldwide urban residential buildings can drop by up to 98% by 2060 (Figure 34-Figure 39). Commercial and public buildings continue to play a large role in the Net Zero scenario in 2060, although total energy demand is drastically decreased. It is worth mentioning that going even lower with the energy intensity of commercial and public buildings often needs further investigation in the usage specialties of different types and therefore needs even more effort than applying renewables onto the building only.

Similar to thermal energy demand, under the Deep Efficiency scenario, energy consumption for hot water can be greatly reduced (Table 10 and Figure 40-Figure 41). Furthermore, when hot water energy consumption is examined across different scenarios, it can be seen that if best practices are followed, global hot water energy consumption can be lowered by 60% by 2060 compared to 2022. At the same time, the Moderate efficiency scenario results in an 8% rise in global hot water related final energy consumption, whereas the Frozen efficiency scenario results in an 85% increase. In the Deep efficiency scenario, the EU-28 countries and the US has the highest potential (55% reduction compared to 2022). Hot water-related energy consumption in China, on the other hand, will rise even in the Deep efficiency scenario (by 10%), and will rise dramatically in the Moderate efficiency scenario (+79%) and the Frozen efficiency scenario (+168%). This can be explained by China's anticipated growth in volumetric hot water use.

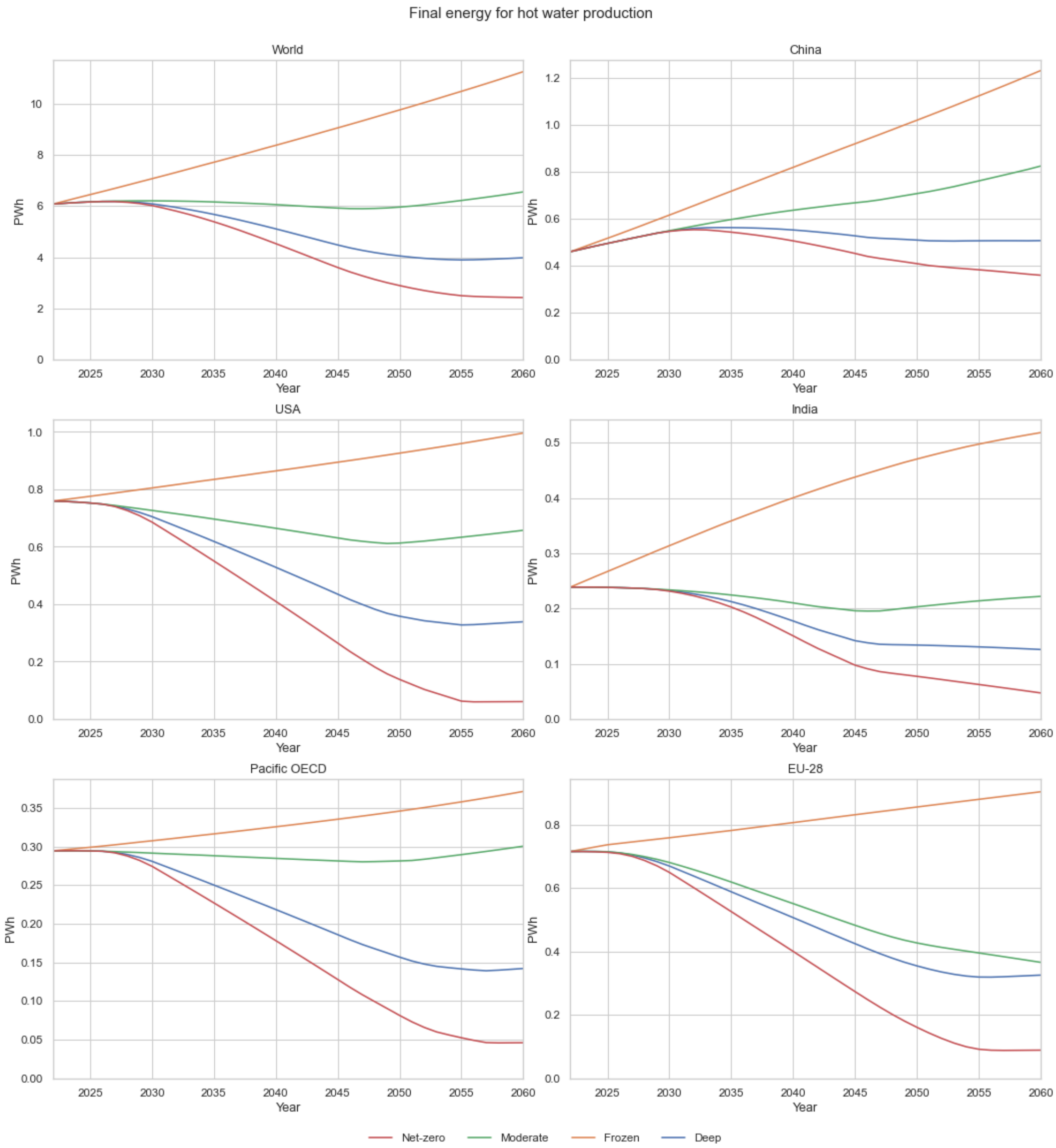


Figure 40. Final energy consumption for hot water production in focus countries according to the three scenarios.

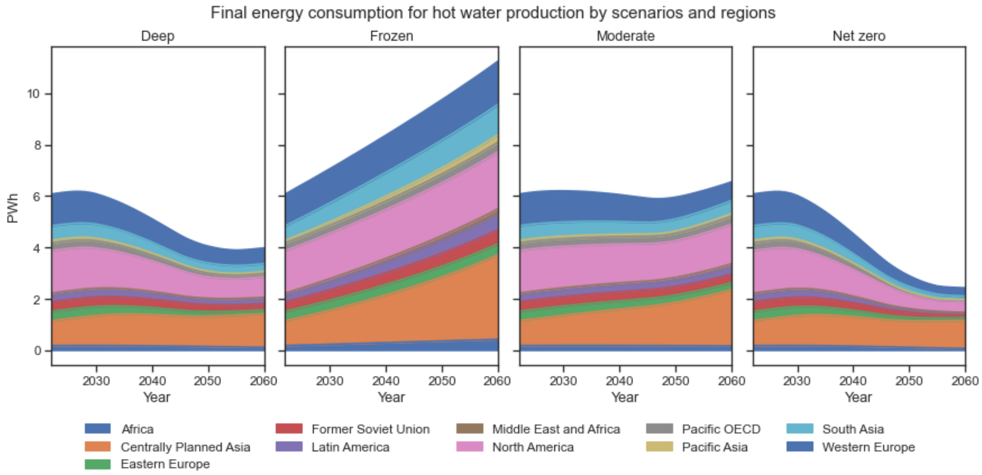


Figure 41. Share of building category within the World final energy consumption for hot water production in PWh.

Table 10. Results for final energy use of hot water production in the key regions and the World.

Scenario	Baseline	Moderate Efficiency		Deep Efficiency			Net Zero			Frozen		
	2022 PWh	2060 PWh	Δ% to 2022	2060 PWh	Δ% to 2022	Δ% to Moder.	2060 PWh	Δ% to 2022	Δ% to Moder.	2060 PWh	Δ% to 2022	Δ% to Moder.
China	0.46	0.82	+79%	0.51	+10%	-39%	0.36	-22%	-56%	1.23	+168%	+49%
EU-28	0.72	0.37	-49%	0.32	-55%	-11%	0.09	-87%	-76%	0.90	+26%	+146%
India	0.24	0.22	-7%	0.13	-47%	-43%	0.05	-80%	-79%	0.52	+117%	+134%
Pacific OECD	0.29	0.30	+2%	0.14	-52%	-53%	0.05	-84%	-85%	0.37	+26%	+24%
USA	0.76	0.66	-13%	0.34	-55%	-48%	0.06	-93%	-91%	1.00	+31%	+52%
World	6.08	6.56	+8%	3.99	-34%	-39%	2.43	-60%	-63%	11.25	+85%	+72%

4.1.3 Estimating hourly building energy demand

The hourly profile is calculated based on annual demand, user profile, and ambient temperature. To calculate hourly demand profile, we use Equation 14-Equation 36. The findings of the study show that similar to annual demand, the hourly profile also substantially reduced in the Deep efficiency and Net-zero scenarios. However, the Frozen and Moderate efficiency scenarios show a significant increase in the global final energy demand.

In the hourly profiles, the seasonality factor in energy demand becomes prominent- precisely, we see that the demand for space heating and hot water peaks during the winter season (November to February), whereas the cooling demand peaks during the summer season (April to August). It must be emphasized that the majority of the buildings are located in the northern hemisphere, therefore the global hourly profiles includes less significantly temporal characteristics of the weather-dependency of energy demand. Since because of methodological considerations the shape of the profiles do not change among the scenarios and years in the HEB model, now we are focusing on analyzing the relative intra-annual changes of the demand for each end-uses rather presenting the absolute values (Figure 42-Figure 50).

The space heating demand was modelled to have its global maximum in December and January when the air temperature is the lowest globally (Figure 43). Again, due to the spatial distribution of worldwide buildings, the hourly profiles reflects rather the typical profiles over the northern hemisphere. For this reason, the lowest heating demand occurs in July. Between maximum and minimum, the demand for space heating can drop by 93%.

The cooling demand also show remarkable seasonality, although the corresponding demand was found to be more balanced throughout the year. The slighter seasonality could be underlined that the percent deviation for this parameter is only 64%, which means that cooling need persist in each month of the year globally. Based on Figure 44, the global peak for space cooling occurs in May. It is mostly attributed to buildings located in South Asia (incl. India; see Figure 47-Figure 48), Middle East-Africa and Africa. Especially in India and developing countries in the low and mid-latitudes, the energy for space cooling is demanded nearly during the entire year. Nevertheless, on global level a definite minimum is outlined between November and March. Since there are only few buildings in climate zones where both the heating and cooling demand is large, the energy demand for these end-uses were simulated to typically be in counter-phase over the year.

However the space heating and cooling demand seems to co-exist during relatively a short period across the year, the need for hot water production distributes evenly between the days (Figure 45). Its modelled maximum occurs in January, while the minimum is seen in July. The percent deviation of the time series of hot water demand is only 24%, which confirms the relatively low annual variation. Except for the slight temporal variability, the hot water production profile has similar annual shape as that of space heating, which is the consequence of its negative correlation with the air temperature. As for other end-uses, the spikes in the profiles indicates the shift of low and high demand phases between weekdays and weekends.

Analyzing the hourly demand profiles by climate zones (Figure 46), it is observed that to increase the energy efficiency of buildings, very different, climate-specific actions are needed to be taken. For example, for buildings in the 'Minor heating and cooling' climate zone of Latin America, the focus must be on finding solutions to decrease the need chiefly for hot water production. Despite the major rise of floor area in this region, the results show that with constructing energy efficient buildings (i.e., Deep efficiency case), the hot water demand can be reduced remarkably in this part of Latin America. On the other hand, due to the less energy-efficient and extensive building stock in South Asia, there could be large demand by 2060, for instance, in case of space cooling in the 'Only cooling' category (Figure 46). In the developed regions (e.g., North America and Western Europe), large reductions can be achieved considering a favorable share of advanced buildings. This is true even when the climate forcing would generate high loads for space heating (i.e., in winter) and cooling (i.e., in summer).

As it was concluded for developing regions, despite the major reductions in the demand, buildings do not seem to decrease entirely the need for energy. For example, India is expected to increase its buildings stock by 2060. Therefore, despite the ambitious energy efficiency policies considered in the Deep efficiency scenario, substantial demand still remains for each of the three end-uses. In January, the largest (unreduced) need is seen for the space heating in the evening and space cooling in the daytime. In July, the compensation of space cooling looks to be the highest challenge (Figure 47Figure 48). At this point, it is important to mention that India is rich of solar energy, and hence some of the demand could be supplied by clean energy. For this reason, there is a need to better understand of how much and in which periods of the year the solar energy is able to balance the demand side in India and in other modelling regions (see Section 4.3.).

In the USA, in which the building stock is anticipated to be more energy efficient by 2060, climate change and increase in the demand for space cooling also poses a major challenge (Figure 50) towards reaching low energy efficiency level. On the other hand, if advanced buildings dominate the entire building sector, the energy need for hot water production and space heating can be pushed down in the 'critical' months in the USA by the end of the modelling period (Figure 49).

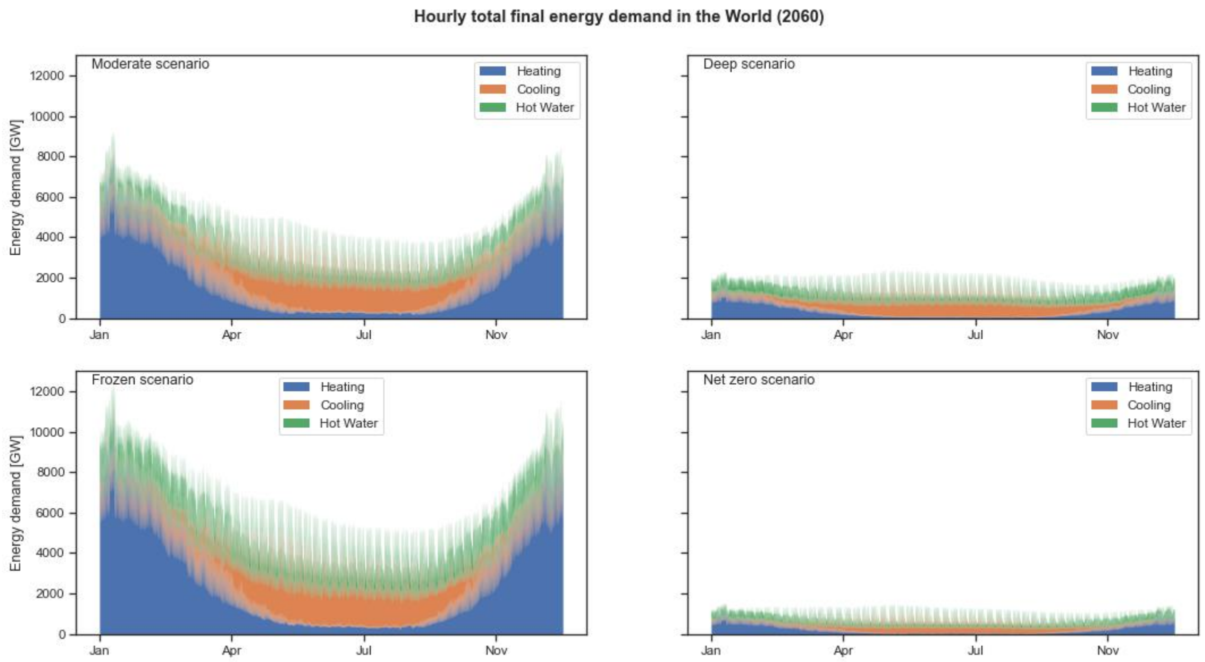


Figure 42. Hourly total energy demand on global level in 2060, by end-uses and scenarios.

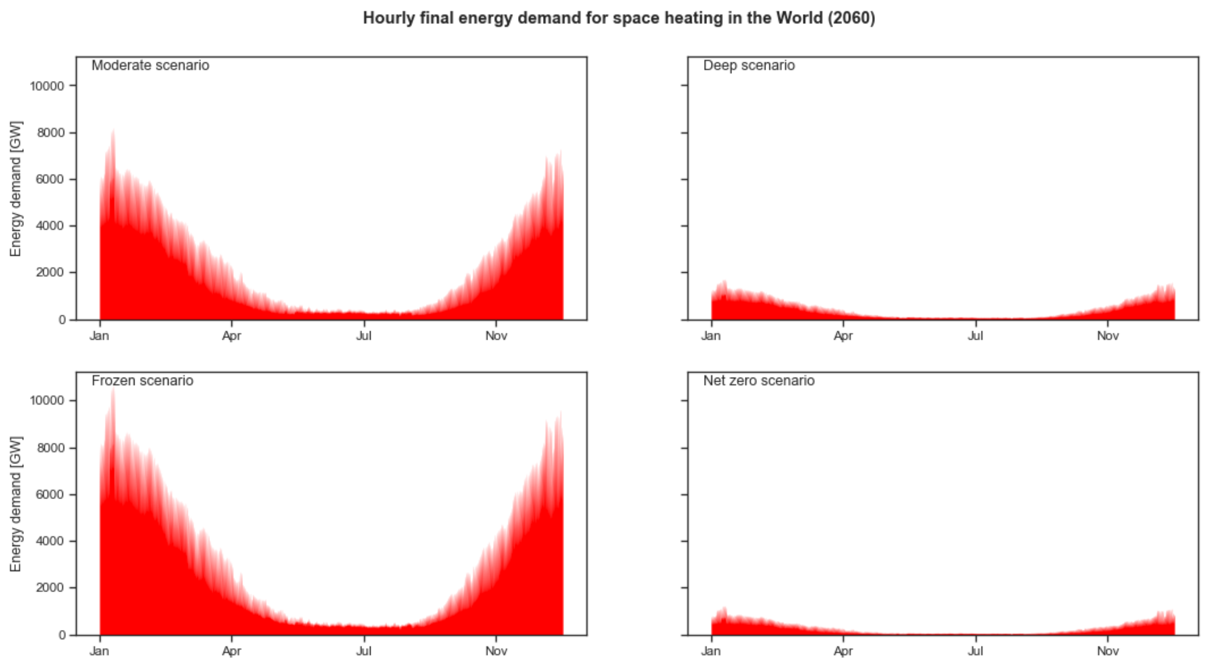


Figure 43. Hourly final energy demand for space heating on global level in 2060, by different scenarios.

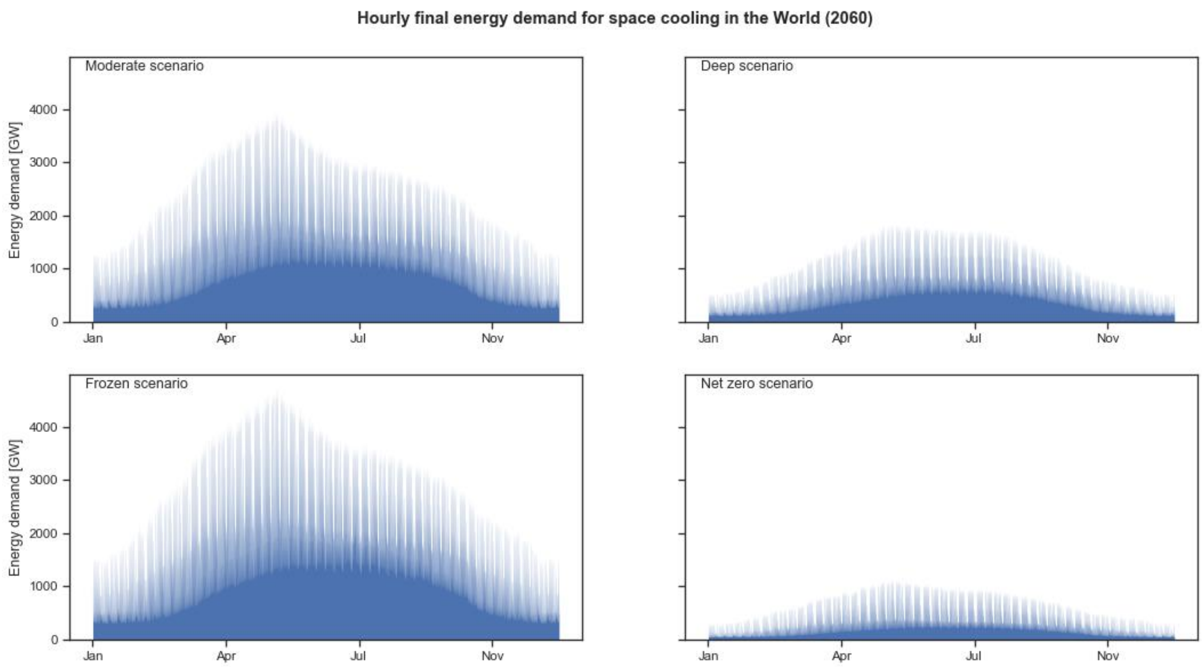


Figure 44. Hourly final energy demand for space cooling on global level in 2060, by different scenarios.

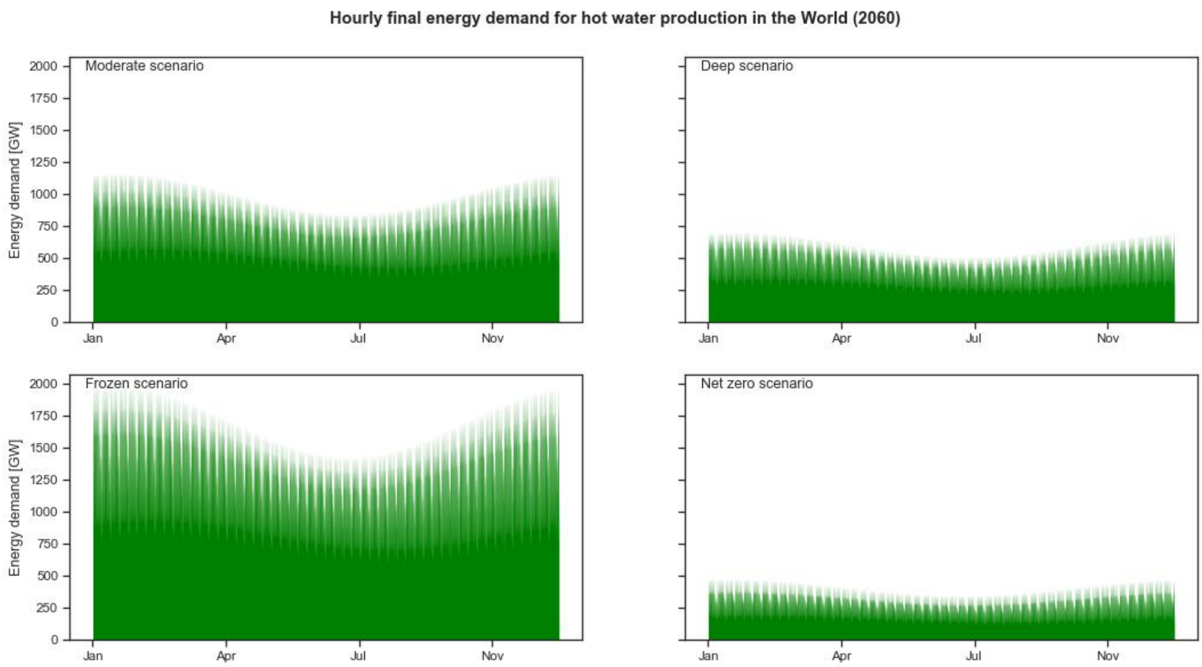


Figure 45. Hourly final energy demand for hot water production on global level in 2060, by different scenarios.

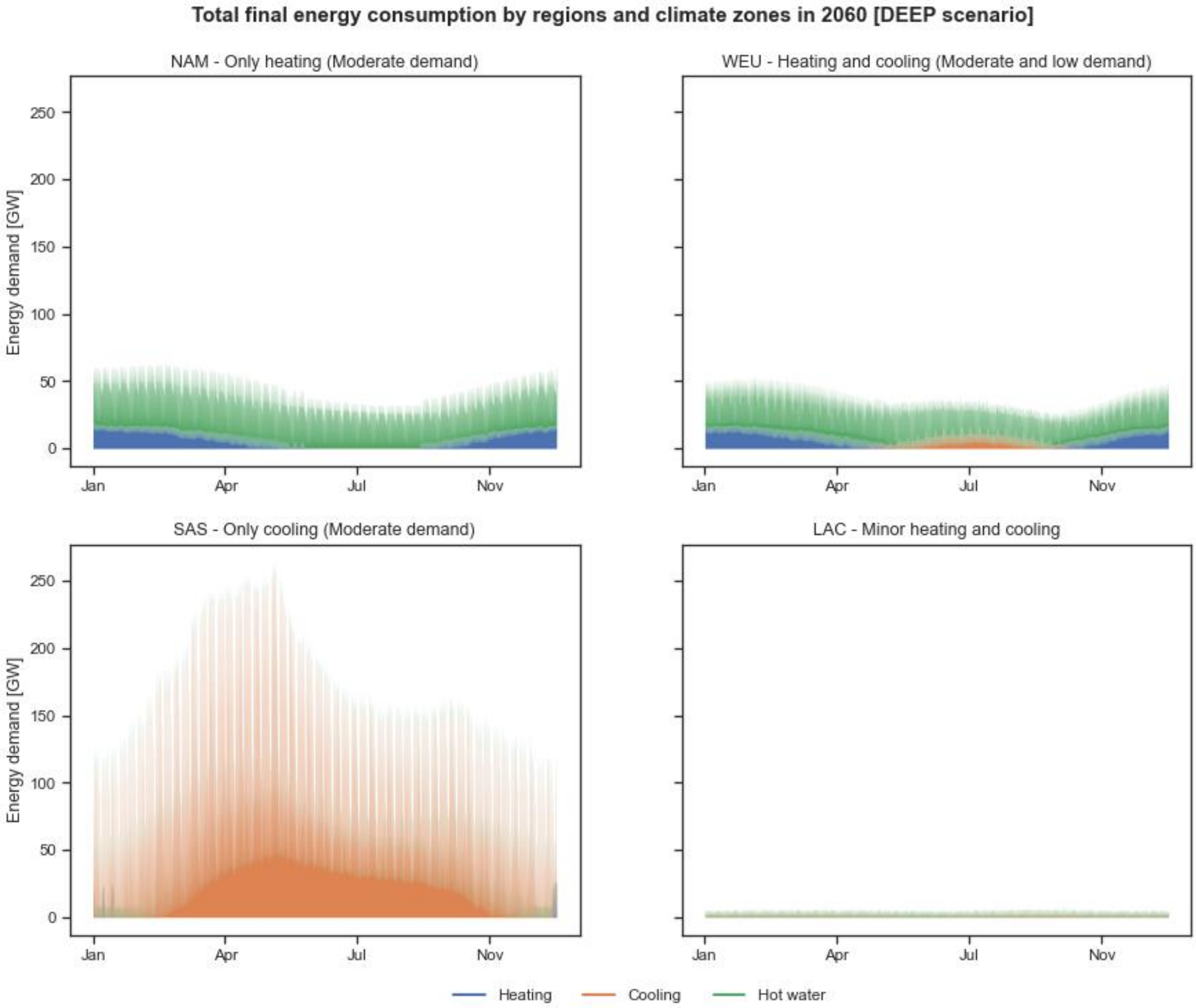


Figure 46. Hourly final energy consumption for space heating, cooling and hot water production in given regions and climate zones predicted by the DEEP scenario 2060 (in PWh).

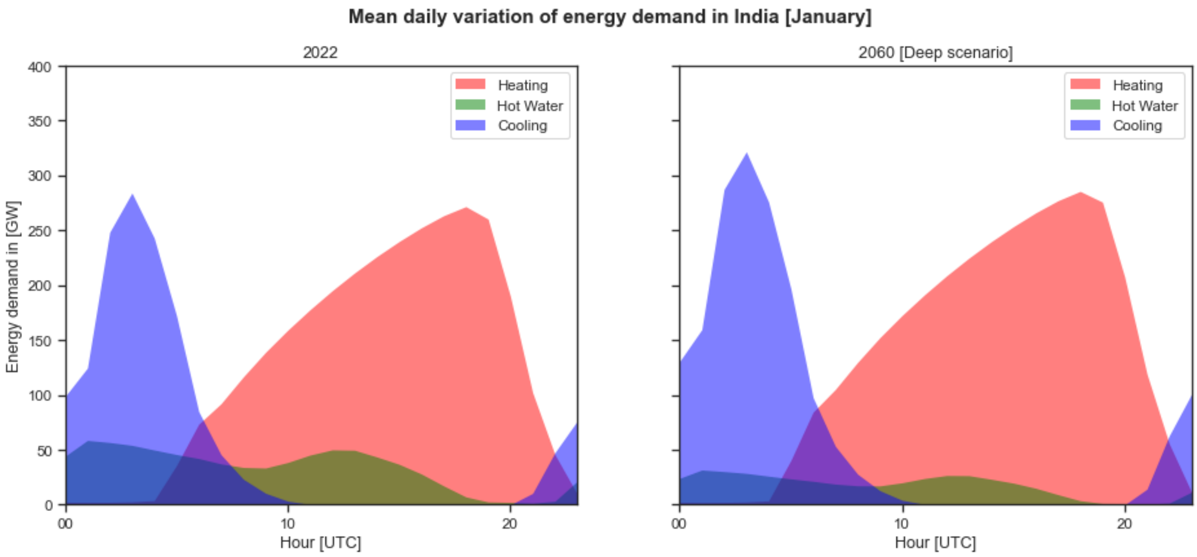


Figure 47. Comparison of the mean daily variation of the end-use energy demand in India in January of 2022 and 2060 according to the Deep efficiency scenario.

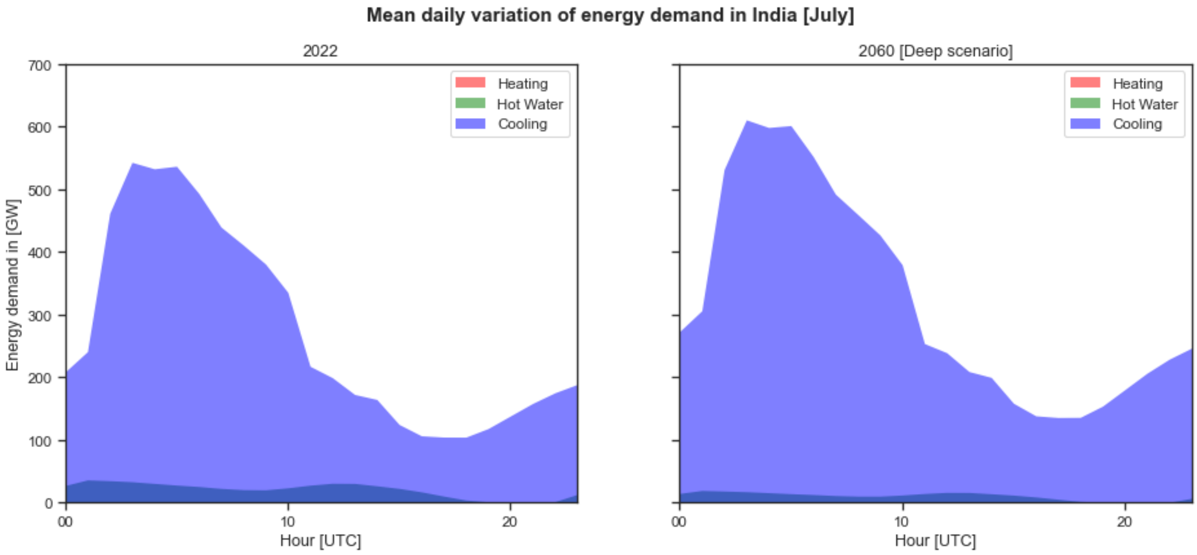


Figure 48. Comparison of the mean daily variation of the end-use energy demand in India in July of 2022 and 2060 according to the Deep efficiency scenario.

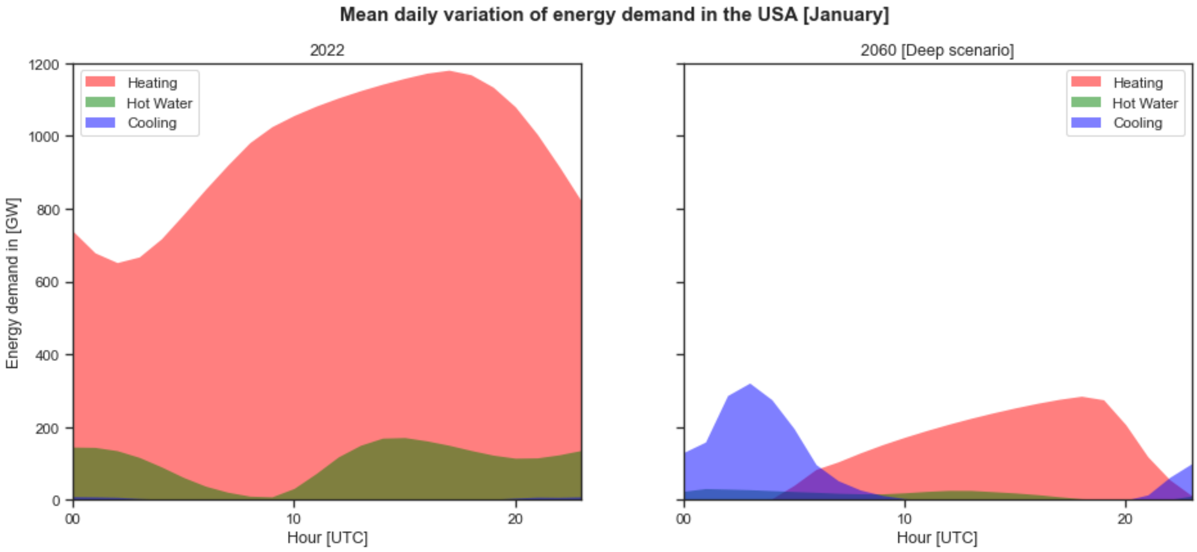


Figure 49. Comparison of the mean daily variation of the end-use energy demand in the USA in January of 2022 and 2060 according to the Deep efficiency scenario.

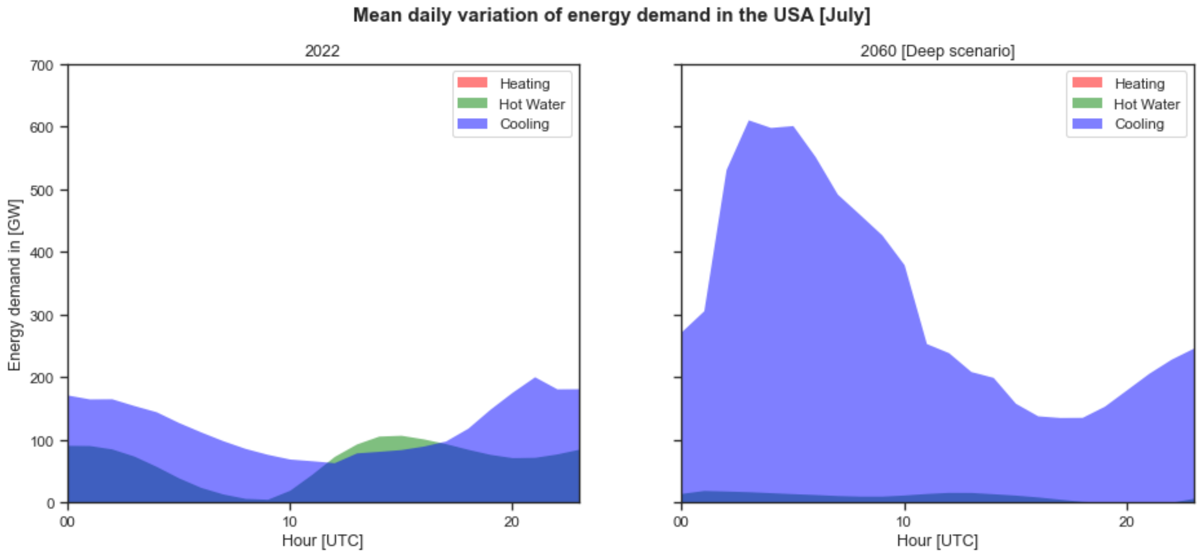


Figure 50. Comparison of the mean daily variation of the end-use energy demand in the USA in July of 2022 and 2060 according to the Deep efficiency scenario.

4.1.4. CO_2 emission potential of the building sector

CO_2 emissions were calculated in two steps: first, the final energy is converted to the primary energy by using primary energy factors (PEF) (Urge-Vorsatz et al., 2012); then we use the emission factors of primary fuels to calculate CO_2 emissions for different types of fuels. To obtain regional emission factors, country level emission factors were aggregated. For the country level emission factors various sources were used, including the global Greenhouse Gas Inventory dataset of the IPCC for fuel mix-independent energy carriers (e.g., natural gas, lignite), national greenhouse gas inventories (e.g., DISER, 2020; Netherlands Enterprise Agency, 2020) and different publications (e.g., Werner, 2017). In our model, it is assumed that the emission factors are constant for space heating and cooling from 2022 to 2060.

By applying these steps, the findings of HEB model show that globally the building related CO_2 emission could be reduced remarkably, but even if applying very ambitious energy efficiency policies, the emission reduction is only 50% (Table 11; Figure 51). On the other hand, if the current trends are projected for the future, a 39% growth is expected by 2060. Regionally, the reduction potential could much higher than that of globally. It was found for the EU, USA and Pacific OECD, with reductions over 80% in the Deep scenario. In China, the best achievable emission decrease was modelled to be around only 50%. For India, more unfavorable numbers were predicted. The results indicate that despite the assumed ambitious policies, it seems to be unrealistic to reduce the CO_2 emission due to the huge increase in the floor space (Figure 32).

Highlighting the space heating and cooling among the end-uses, it was estimated that as the most important sources of building-related energy demand, the highest emission is connected to them as well. As our results suggest, the corresponding reduction potential for CO_2 emission could have the same magnitudes as the ones presented in Table 11. In other words, the best potential is outlined in the developed countries (80-85% as compared to the current level), while the least decreases (or even surpluses) are expected for India and other South Asian countries (Table 12; Figure 52). Nevertheless, it must be noted that most developed countries are heating-dominated for which the demand is anticipated to shrink in the next decades as a consequence of climate change. While in the developing

Asian, African and Latin American areas, the global warming might result in increased cooling loads (in most, they are already cooling-dominated) and emissions that will be mitigated with only huge efforts.

Table 11. Total building-related CO_2 emission in the key regions and the World.

Scenario	Baseline	Moderate Efficiency		Deep Efficiency			Frozen		
	2022 10^6 kg	2060 10^6 kg	Δ% to 2022	2060 10^6 kg	Δ% to 2022	Δ% to Moder.	2060 10^6 kg	Δ% to 2022	Δ% to Moder.
China	2.16	3.63	+68%	1.11	-48%	-69%	4.93	+128%	+36%
EU-28	0.87	0.21	-75%	0.13	-85%	-37%	0.94	+7%	+335%
India	1.02	2.91	186%	1.13	11%	-61%	3.56	+250%	+22%
Pacific OECD	0.44	0.34	-21%	0.08	-81%	-76%	0.43	-2%	+25%
USA	1.27	1.13	-10%	0.21	-84%	-82%	1.38	+9%	+22%
World	9.3	12.91	+39%	4.67	-50%	-64%	18.1	+95%	+40%

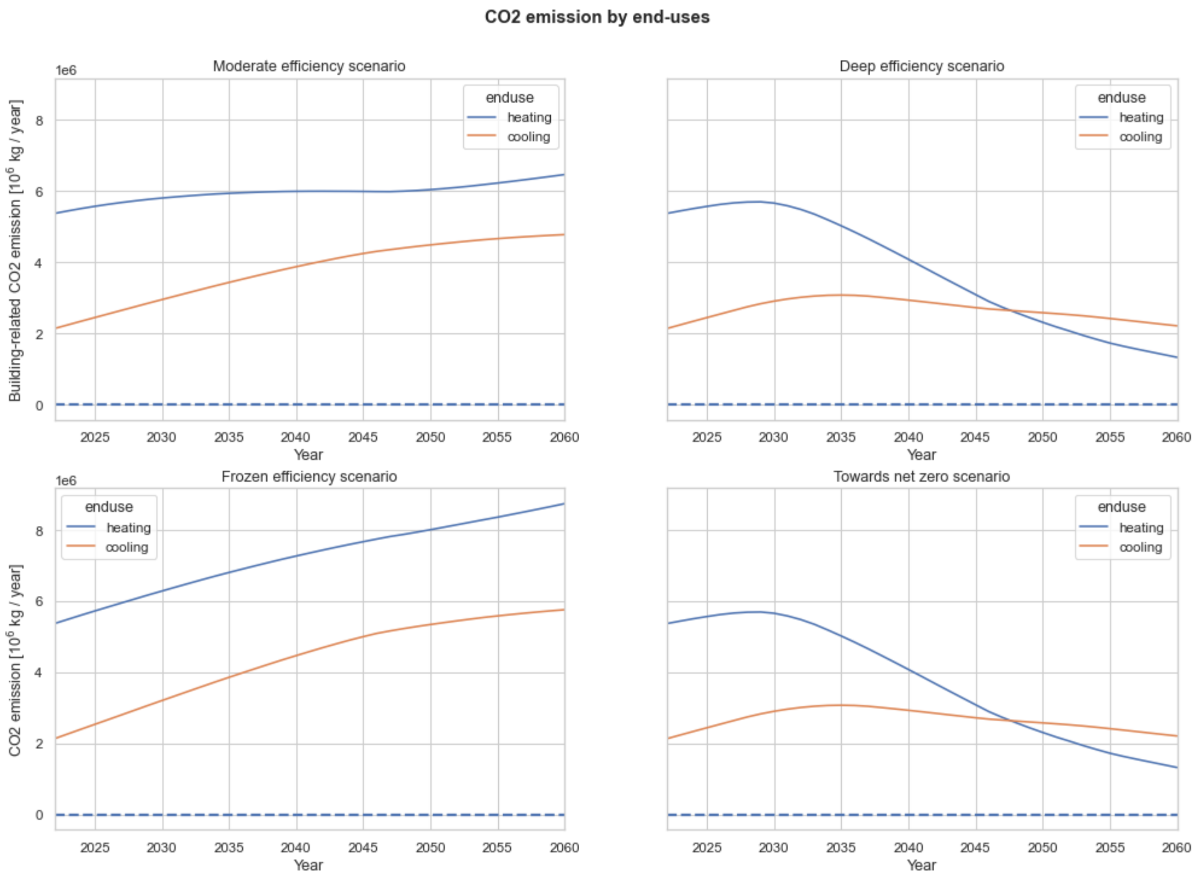


Figure 51. CO_2 footprint of building energy demand over the modelling period, by end-uses and scenarios.

Table 12. Space heating and cooling CO_2 emission in the key regions and the World.

Scenario	Baseline	Moderate Efficiency		Deep Efficiency			Frozen		
	2022 10^6 kg	2060 10^6 kg	Δ% to 2022	2060 10^6 kg	Δ% to 2022	Δ% to Moder.	2060 10^6 kg	Δ% to 2022	Δ% to Moder.
China	1.98	3.37	+70%	0.95	-52%	-72%	4.45	+125%	+32%
EU-28	0.69	0.14	-80%	0.07	-90%	-51%	0.71	+2%	+410%
India	0.93	2.87	210%	1.08	17%	-62%	3.36	+263%	+17%
Pacific OECD	0.35	0.28	-21%	0.05	-87%	-84%	0.32	-10%	+15%
USA	1.09	1.00	-8%	0.14	-88%	-87%	1.15	+6%	+16%
World	7.49	11.22	+50%	3.52	-50%	-67%	14.5	+95%	+29%

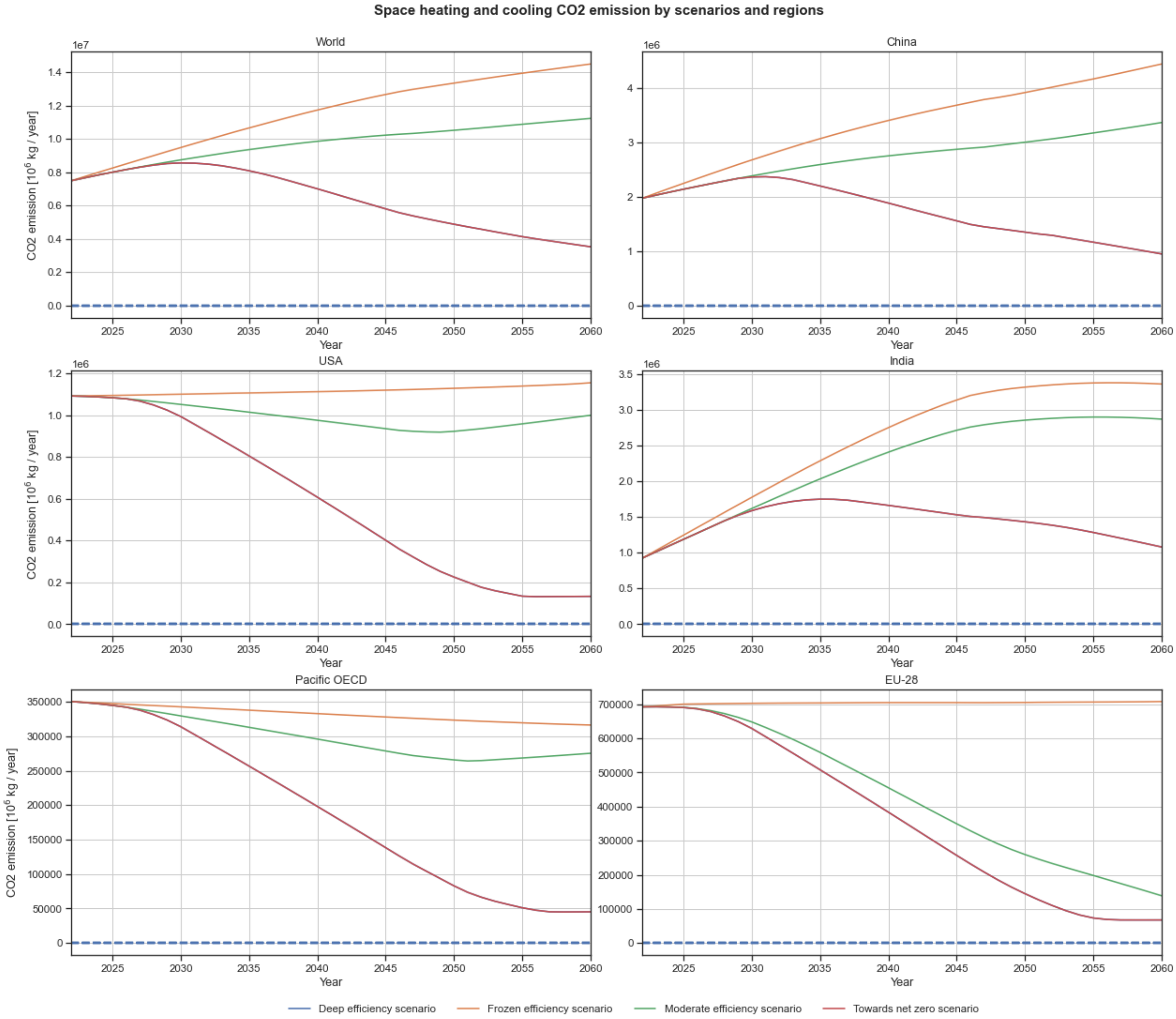


Figure 52. CO_2 footprint of space heating and cooling energy demand over the modelling period in the key regions, by end-uses and scenarios.

4.1.5. Sensitivity analysis

HEB model is quite data-intensive, and moreover, it relies on diverse socio-economic statistical data sources and building stock-related assumptions. Thus, to assess the influence of these input data and assumptions on the results of the model, a sensitivity analysis is conducted. The aim of conducting a sensitivity analysis is twofold: first the influence of fixed assumptions is investigated, and then the effect of scenario-specific parameters is analyzed through various adjustments in the most essential assumptions. Because the Deep Efficiency scenario has the highest effect on the final energy demand, it is utilized to demonstrate the sensitivity analysis results in the following.

Retrofit rate:

The retrofit rate is a major factor in upgrading existing stock to a higher level with lower energy usage. Many factors, including as construction market capacity, economic constraints, and competing investment possibilities, limit retrofit rates. A faster retrofit rate can be one of the variables in achieving a high-efficient building stock level. The retrofit rate in each country/region is projected to increase from 1.4 percent to an accelerated level in the calculations. However, for the EU member states the retrofit rate varies as per country and it ranges from 0.5-3%. The retrofit rate is set to 3% in developed countries, and 1.5-1.6% in developing countries. The year when the accelerated rate is achieved (shift year) is set to 2027 assuming a short period of market preparation. In the sensitivity analysis, both the accelerated rate, and the shift year are assessed in terms of influence on the total energy demand of the building stock. Figure 53 shows that the increased level of accelerated retrofit rate can contribute to lower energy demand at the end of the modelling period. If retrofit rate is increased by 50%, the final energy demand in 2060 decreases by 25%, while decreasing the retrofit rate to 50% would lead to an increased final energy demand by 9%. On the other hand, delay in the shift year hardly influences the achieved energy consumption level in 2060. This highlights the importance of retrofitting buildings at the end of the modelling period that were newly built or retrofitted at the beginning but at a lower efficiency level.

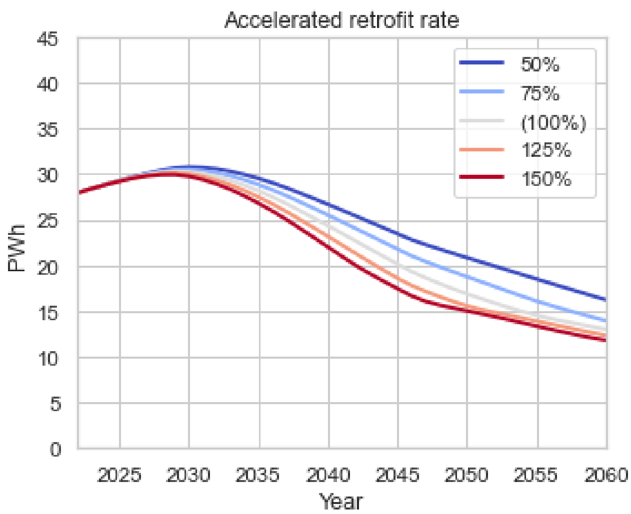


Figure 53. Sensitivity of the total final energy consumption to the level of accelerated retrofit rate.

Share of advanced buildings:

The time when severe building efficiency policies are implemented is one of the major distinctions between the scenarios. All new and modified buildings are anticipated to be high-efficient after this time. The year 2027 was picked as an ambitious target year for the policies in most of the regions in the Deep Efficiency scenario (baseline for the sensitivity analysis). The impact of delaying the implementation of such policies is demonstrated in the following section. A five-year, ten-year, and twenty-year wait, as well as an urgent introduction (5 years earlier), are all examined. Figure 54 shows how the time delay has a significant impact on the final energy demand that can be met by 2060. A 5-year delay would increase the final energy demand in 2060 by 32%, while a 10- and 20-year delay would increase it by 72% and 141% respectively. On the other hand, a rapid act (5 years earlier) would lead to a 26% decrease in the final energy demand by 2060.

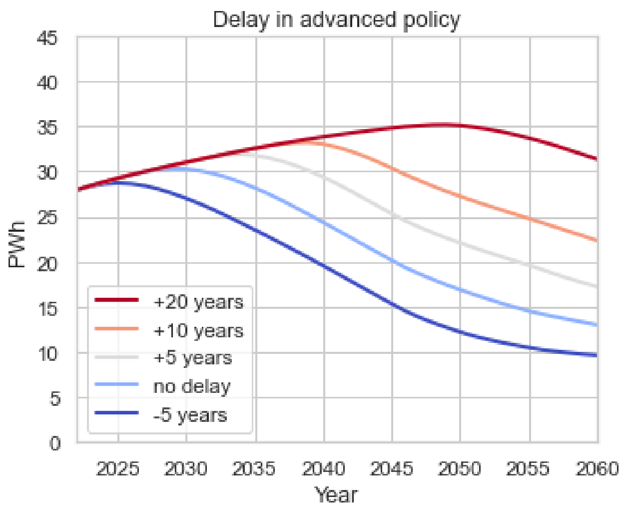


Figure 54. Sensitivity of the total final energy demand to the delay in introduction of advanced requirements for new and retrofitted buildings.

Energy intensity:

Finally, the impact of different levels of building efficiency on total final energy use is investigated. The state-of-the-art technical potential on a building level that has been proved to be possible around the world is represented by advanced retrofit and advanced new building. However, if the rule does not require this level, it may have an impact on the overall final energy demand that can be met until 2060.

The specific final energy demand of advanced buildings (new and retrofitted) is increased to 150%, 200% and 250% and decreased to 50% in all regions. In Figure 55, the sensitivity of the total final energy demand is plotted. The change in the specific energy demand directly influences the total, since in this scenario, most of the building stock corresponds to the advanced level by 2060. If the specific energy demand is increased to 250% the total achieved final energy demand increases by 53%, the lower levels correspond to 35% and 18% increase. On the other hand, decreasing the specific energy demand even more, to 50% leads to a 18% reduction in the total final energy demand of the stock. This supports the importance of high-efficiency policies and clearly shows that lower efficiency levels diminish the potential of the building sector in reducing the total energy demand.

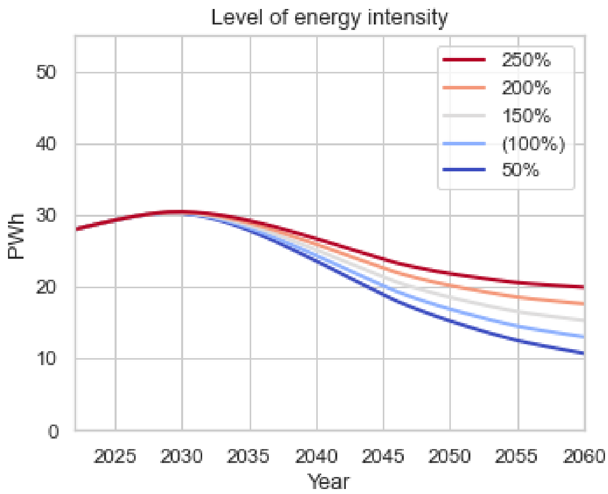


Figure 55. Sensitivity of the total final energy demand to the energy intensity value of advanced new and advanced retrofitted buildings.

4.2. The potential of on-site solar energy production

The modeling activity with the BISE model was intended to address three major questions. First, it was modelled how much the total and utilizable rooftop area will likely to change over the next decades. Secondly, simulations were performed how much solar electric and thermal energy can be potentially produced in key regions of the Worlds, by installing all available rooftop areas with cutting-edge PV/T collectors. Thirdly, the solar energy production of rooftop PV panels was also assessed. Precisely, the PV-related simulations have twofold interest. On the one hand, we shed light via a scenario analysis on how much electric energy is producible if the historical trends of global PV generation are extrapolated to the modeling period. On the other hand, it was calculated how much potential different buildings have in balancing the local energy demand with on-site PV production (see Section 4.3.).

4.2.1. Estimating building rooftop area

As it was concluded in the methodological description of the BISE model, both the total (RA_{total}) and the available roof area ($RA_{PV/T\ syst}$) has pivotal role in determining the technical potential of rooftop solar energy production. The RA_{total}, the horizontal surface area of buildings, was predicted to be the largest for the Centrally Planned Asia (6.8×10^{10} m^2), while the Eastern European region is characterized by the lowest estimated value (2.8×10^{8} m^2) in 2022 (Figure 56). After Centrally Planned Asia, significant RA_{total} values were found for the North America (3.1×10^{10} m^2) and Latin America (2.7×10^{10} m^2).

In regions where the RA_{total} is large in the initial year (e.g., North America, Centrally Planned Asia, Western Europe), the estimated rise during the analysis period was projected to be less intense until than in other regions (e.g., Latin America, Pacific Asia and Middle East Africa). In other words, the building stock is anticipated to increase more in the developing regions resulting in more area could potentially be installed with rooftop solar systems. Due to the outlined tendencies, Latin America and Pacific Asia moved up to have the second (6.2×10^{10} m^2) and third largest RA_{total} (4.8×10^{10} m^2) among the modeling regions by 2060. Nevertheless, the building stock is expected to remain the more extensive in Centrally Planned Asia, with an RA_{total} of $1.126.8 \times 10^{11}$ m^2. On the lower edge, the Eastern Europe region was modelled to include the smallest value (6.2×10^{8} m^2), with only a 8% growth over the 39 years (Figure 56).

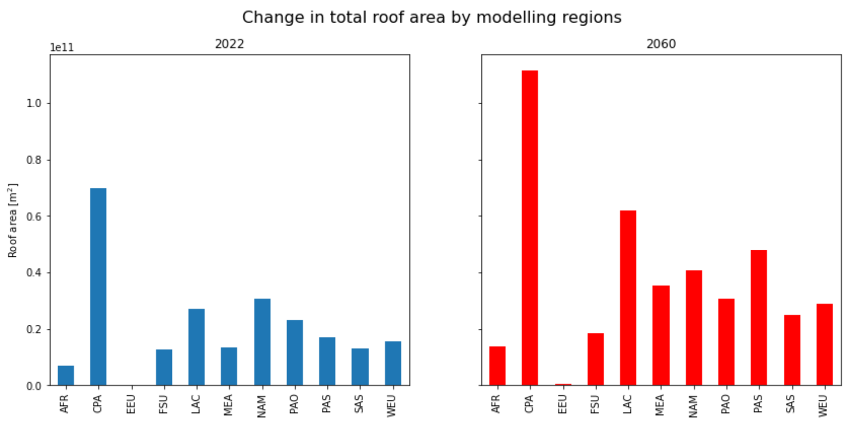


Figure 56. Total roof area in each region in 2022.

In the default BISE runs, the RA_{total} values must be decreased to consider rooftop subareas where the solar energy generation is not possible (e.g., obstructed areas) or results in limited energy yields (e.g., permanently shaded areas). By accounting these factors via the so-called utilization factor (U_F; see Equation 39), the model calculates the physically suitable roof area in each region. By definition, it is prescribed that all available rooftop areas are covered by PV/T collectors. Thus, this area can also be called as the area of the PV/T systems ($RA_{PV/T\ syst}$).

In general the $RA_{PV/T\ syst}$ was projected to be 25–32% of the RA_{total} (Figure 57). In other words, about one third of the building rooftops seem to be applicable to be install with solar systems and to efficiently supply solar energy. Analyzing the $RA_{PV/T\ syst}$ by buildings types, it is clearly seen that single family buildings have the largest utilizable areas in most regions for installing for deploying solar arrays. In the Pacific OECD region, however, multifamily buildings seem to be the most suitable for this purpose. The dominance of residential rooftops are attributed to two factors. First, the building stock was estimated to be composed of residential buildings more dominantly relative to commercial/public buildings. Secondly, less importantly, the U_F was found to be lower for commercial/public building types (hypothesized with flat roofs), which results in smaller building-specific installation potential (i.e., lower potential for same rooftop area) for these buildings.

By 2060, the most roof area was projected to be available on residential buildings, although in the developed regions, the share of commercial/public buildings in the $RA_{PV/T\ syst}$ could show remarkable expansion over the analysis period. Quantitatively, the share of single family building in the $RA_{PV/T\ syst}$ was predicted to be the largest in Africa (81%; 4.8×10^{9} m^2). In parallel, the acceleration of the commercial rooftops was found to be highest in the Pacific OECD (62%; 7.8×10^{9} m^2) and Western Europe (63%; 7×10^{9} m^2) by 2060. Naturally, similarly to the RA_{total}, the estimated is also the largest (lowest) in Centrally Planned Asia (4.5×10^{10} m^2) (Eastern Europe; 1.2×10^{8} m^2) (Figure 57).

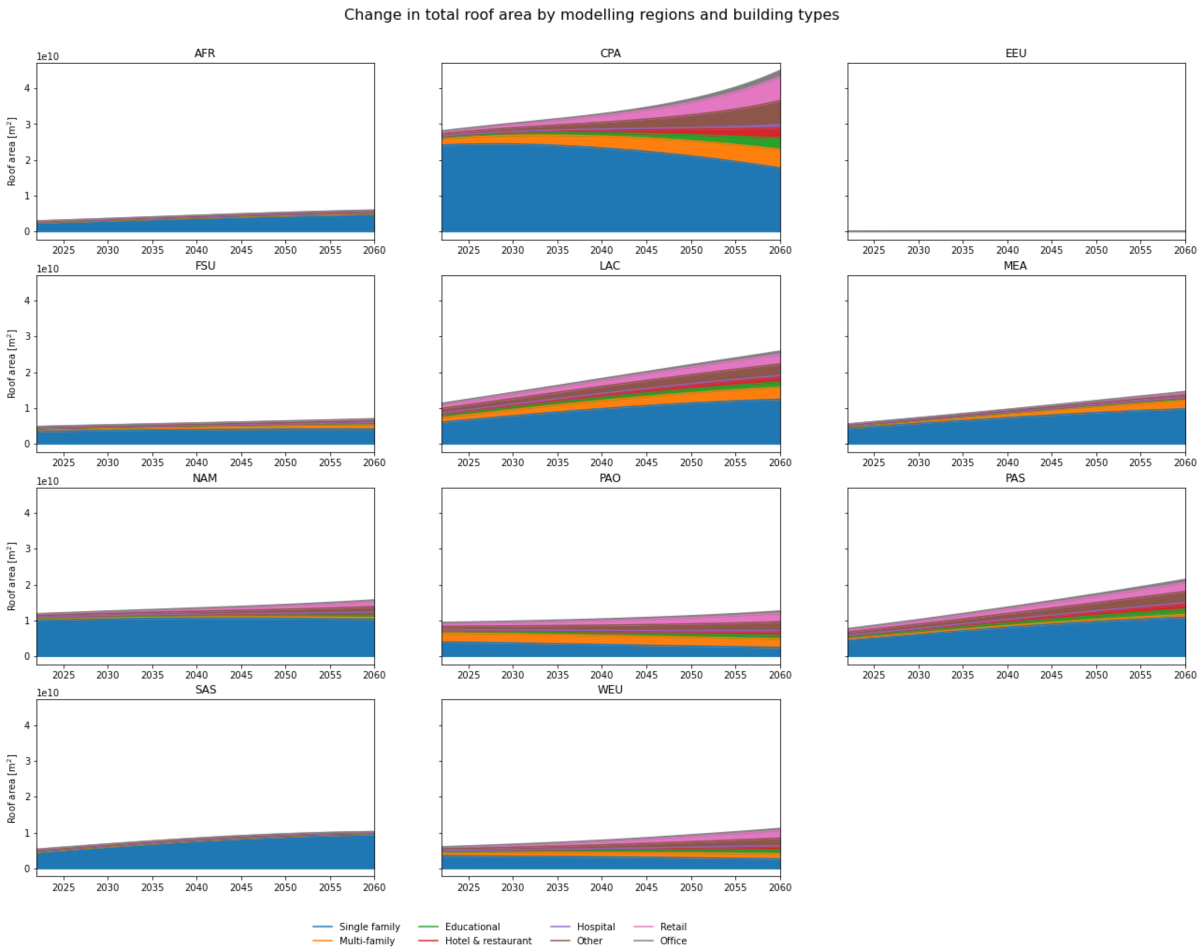


Figure 57. Projected changes of solar system area by regions and building type between 2022 and 2060.

4.2.2. Estimating inter-annual building solar energy supply

It can be concluded based on the comparison of Figure 57 and Figure 58 that the technical potential of PV/T electricity generation, as it is expected theoretically, varies in proportion to the $RA_{PV/T\ syst}$ values. As a direct consequence of this linear dependence, the largest $E_{EL\ total\ supp}$ emerge in Centrally Planned Asia (7.4 PWh) and North America (3 PWh) regions in 2022. For the same reasons, the most pronounced $E_{EL\ total\ supp}$ is expected to be in Centrally Planned Asia (11.9 PWh), Latin America (6.6 PWh), Pacific Asia (4.9 PWh) and Middle East Africa (4.6 PWh) regions by the end of the analysis period.

Such regions as Centrally Planned Asia, Latin America, Pacific Asia and Middle East Africa show the largest increase between 2022 and 2060, with annual growth 0.12, 0.10, 0.08 and 0.07 PWh/year, respectively. In relative sense, these improvements means overall changes between 130–180% for these emerging regions. Compared to these ambitious growths, the mean increase of $E_{EL\ total\ supp}$ was modelled to be only about 85% considering all regions. Owing to the outlined tendencies, 44.7 PWh electric energy may technically be supplied by rooftop-integrated PV/T collectors on global level by 2060.

Besides the inhomogeneity in the $RA_{PV/T\ syst}$ estimations, discrepancies in the solar climate (e.g., annual duration of sunshine hours and annual mean of sunlight's incident angle) also affect the modelled $E_{EL\ total\ supp}$ numbers. For example, the difference in the $RA_{PV/T\ syst}$ between was found to be 12-fold in 2022, while the corresponding difference in the $E_{EL\ total\ supp}$ is only 10-fold. This can be interpreted as that the generally larger radiation income in the African region (320 kWh/m^2*year) is slightly better utilized on 1 m^2 of the solar panel ($E_{EL\ supp}$) that of in Centrally Planned Asia (250 kWh/m^2*year). Between the regions, the most significant $E_{EL\ supp}$ was determined for Middle East Africa (294 kWh/ m^2*year), PAO (286 kWh/ m^2*year) and SAS (267 kWh/ m^2*year).

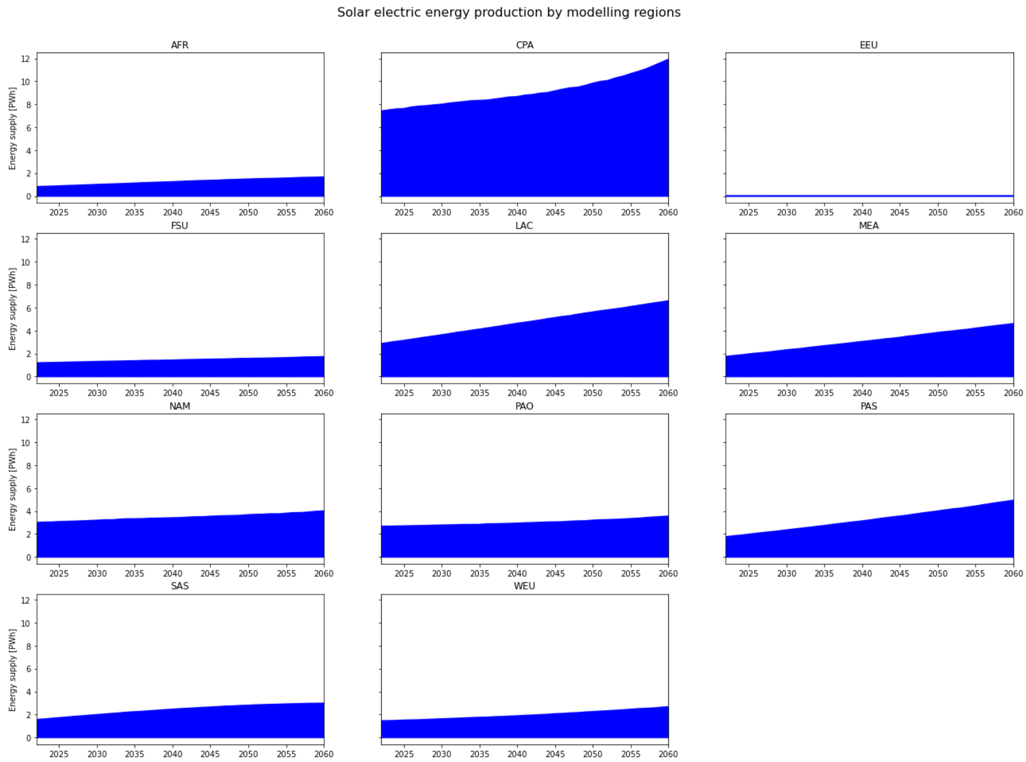


Figure 58. Projected changes of technical potential for solar electric energy supplied by PV/T modules in different regions between 2022 and 2060.

As it was presented in the Figure 58, the regional $E_{EL\ total\ supp}$ values were disaggregated by different building types. Being in line with the conclusions of the Section 4.2.1., the largest potential for electricity production could take place on the rooftops of residential buildings. For 2022, precisely, the BISE model simulated an aggregated $E_{EL\ total\ supp}$ of about 19 PWh for residential buildings (Figure 59). This technical potential, however, is distributed diversely between the regions, showing the highest regional shares in Centrally Planned Asia (36%; 6.4 PWh), North America (14%; 2.6 PWh) and Latin America (9%; 1.5 PWh).

By 2060, the estimated $E_{EL\ total\ supp}$ values could become more balanced in terms of both regionally and in magnitudes. If all physically suitable rooftops would be covered by PV/T collectors by this year, the general increase in the $E_{EL\ total\ supp}$ may be triggered by the production on commercial rooftops. In regions for which the most remarkable $E_{EL\ total\ supp}$ was estimated, the share of commercial buildings in the regional solar electricity production could be over 60% (Pacific OECD: 62% (2.21 PWh); Western Europe: 63% (1.69 PWh)). In most of the developing regions, the largest rooftop solar potential may be associated with the residential buildings. However, in Centrally Planned Asia where the building stock was projected to be the most extended, the corresponding $E_{EL\ total\ supp}$ was estimated to be shrunk (2022: 6.4 PWh; 2060: 4.7 PWh) due the anticipated demolition of residential buildings. Similar decrease is outlined for the single- and multifamily buildings in the Pacific OECD (SF: 1.12 => 0.67 PWh; MF: 0.73 => 0.69 PWh). On rooftops of commercial/public buildings, the $E_{EL\ total\ supp}$ show growth independently of the given region (Figure 59).

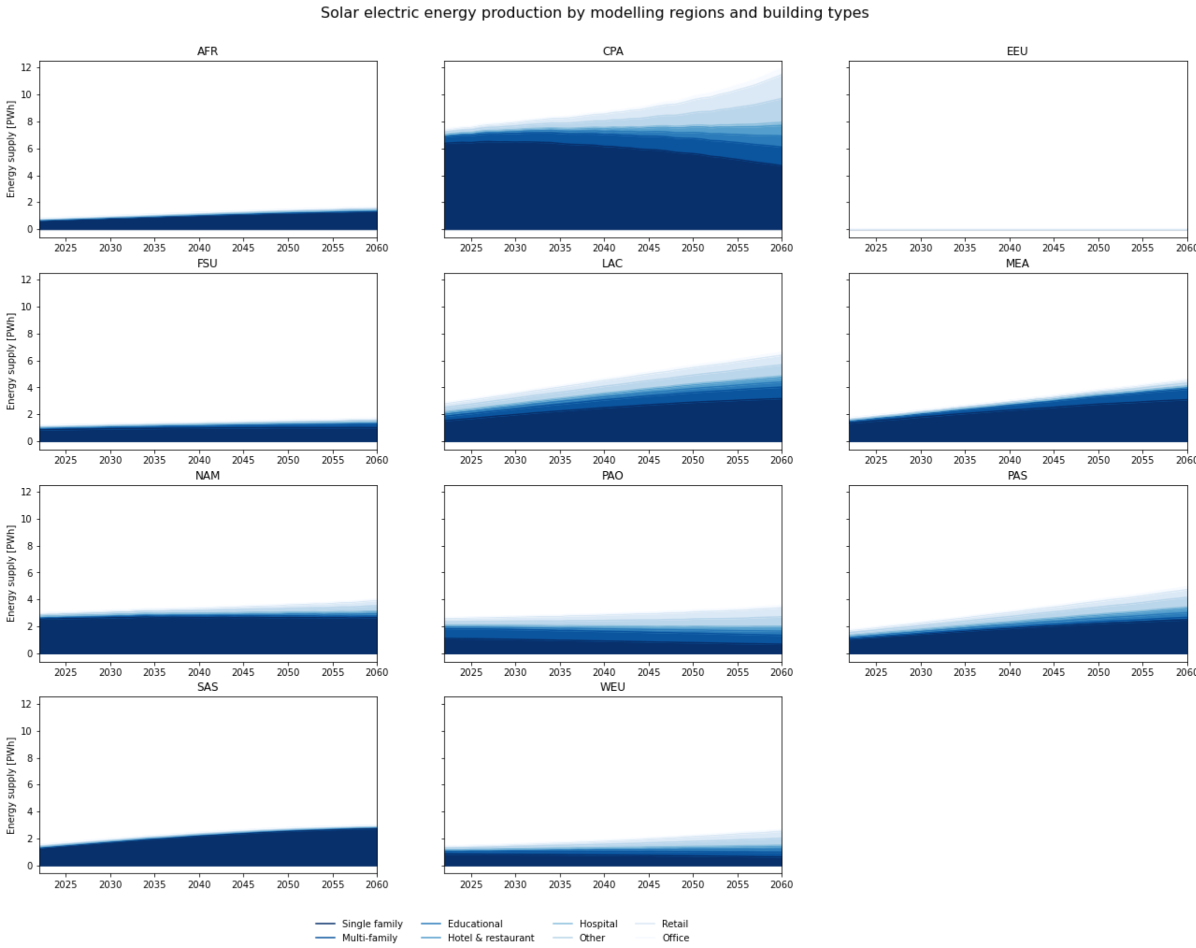


Figure 59. Projected changes of technical potential for solar electric energy supply by PV/T modules in different regions and building types between 2022 and 2060.

Since the production of thermal and electric energy of PV/T collectors occurs simultaneously, the inter-annual tendencies of solar thermal energy supply show strong correlation with that of electric energy supply. For these reason, the inter-regional potentials also seems to be very similar. The highest (lowest) $E_{TH\ total\ supp}$ values (i.e., annual values for 2022) were estimated in the Centrally Planned Asia (15.9 PWh) (Eastern European; 0.05 PWh) regions by 2022 (Figure 60).

As a result of the higher efficiency for thermal energy conversion of the selected PV/T collector "prototype" (see Table 7), the $E_{TH\ total\ supp}$ is more than two times larger than the $E_{EL\ total\ supp}$ numbers. Another crucial modeling experience is that between the two energy outputs of PV/T collectors, the $E_{EL\ total\ supp}$ seems to be more sensitive to the climatic characteristics of a given region. Generally, in regions with high radiation sums and air temperature, the dominance of the $E_{TH\ total\ supp}$ over the $E_{EL\ total\ supp}$ is larger than in temperate and cold climates. For instance, the $E_{TH\ total\ supp}$ / $E_{EL\ total\ supp}$ is equal to 2.4 in South Asia, while this ratio is only 1.25 in the Former Soviet Union. Overall, it can be concluded that there are very few areas across the Word in which the rooftop PV/T systems can produce solar thermal and electric energy with the same effectiveness. In other words, there is an optimum in the weather parameters, which can ensure the best transformation of solar energy to thermal and electric energy by PV/T collectors.

As the Figure 60 suggests, the global $E_{TH\ total\ supp}$ was estimated to rise by 88% between 2022 and 2060. Due to the dynamic of the building stock and the related $RA_{PV/T\ syst}$ magnitudes, the most pronounced growth rates were found again in Middle East Africa (180%), Pacific Asia (165%) and Latin America (130%). On the other hand, the changes in Eastern Europe (10%), Pacific OECD (35%) Former Soviet Union (45%), for example, are anticipated to be below the global mean growth rate of $E_{TH\ total\ supp}$.

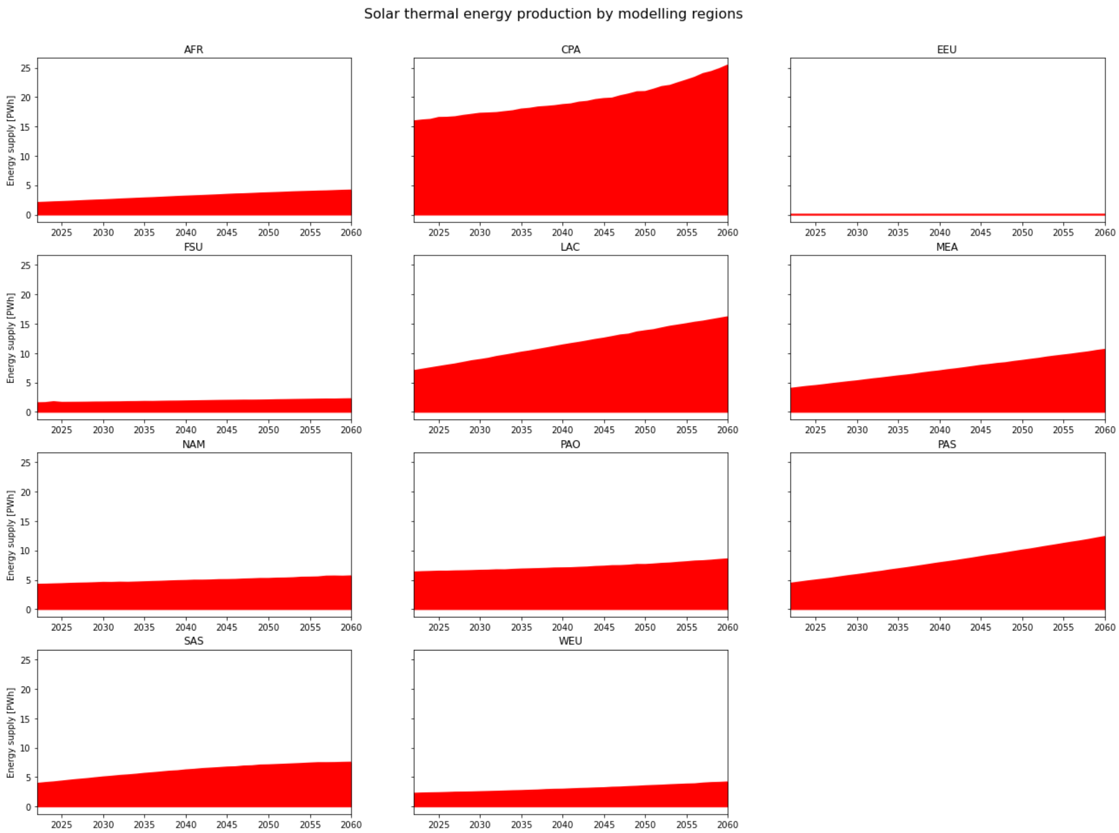


Figure 60. Projected changes of technical potential for solar thermal energy supply by PV/T modules in different regions between 2022 and 2060.

Referring again to the projected composure of the building stock, the largest $E_{TH\ total\ supp}$ could be associated to residential buildings over the entire modeling period (Figure 61). Within the residential building class, the production was found to be more significant for the single-family subcategory. Multifamily buildings has comparable relevance within the "residential sector" only in the Pacific OECD region (SF: 2.6 PWh, MF: 1.7 PWh; both in 2022), however, with shrinking potential towards 2060. In 2022 the share of commercial/public buildings in the $E_{TH\ total\ supp}$ was found to be 5% (EEU)–35% (LAC) globally.

By 2060, the boom of the $E_{TH\ total\ supp}$ is attributable to the tertiary rooftops of developing regions. There is an agreement in these regions that the office and retail buildings could be key in exploiting the possibilities in generating on-site solar thermal energy. In regions where the building stock is expected to be more static, the residential buildings could have the primary importance in solar (thermal) energy production. The African region seems to be an exception, which includes developing economies, but the largest $E_{TH\ total\ supp}$ was modelled for single family buildings (80%; 3.4 PWh) (Figure 61).

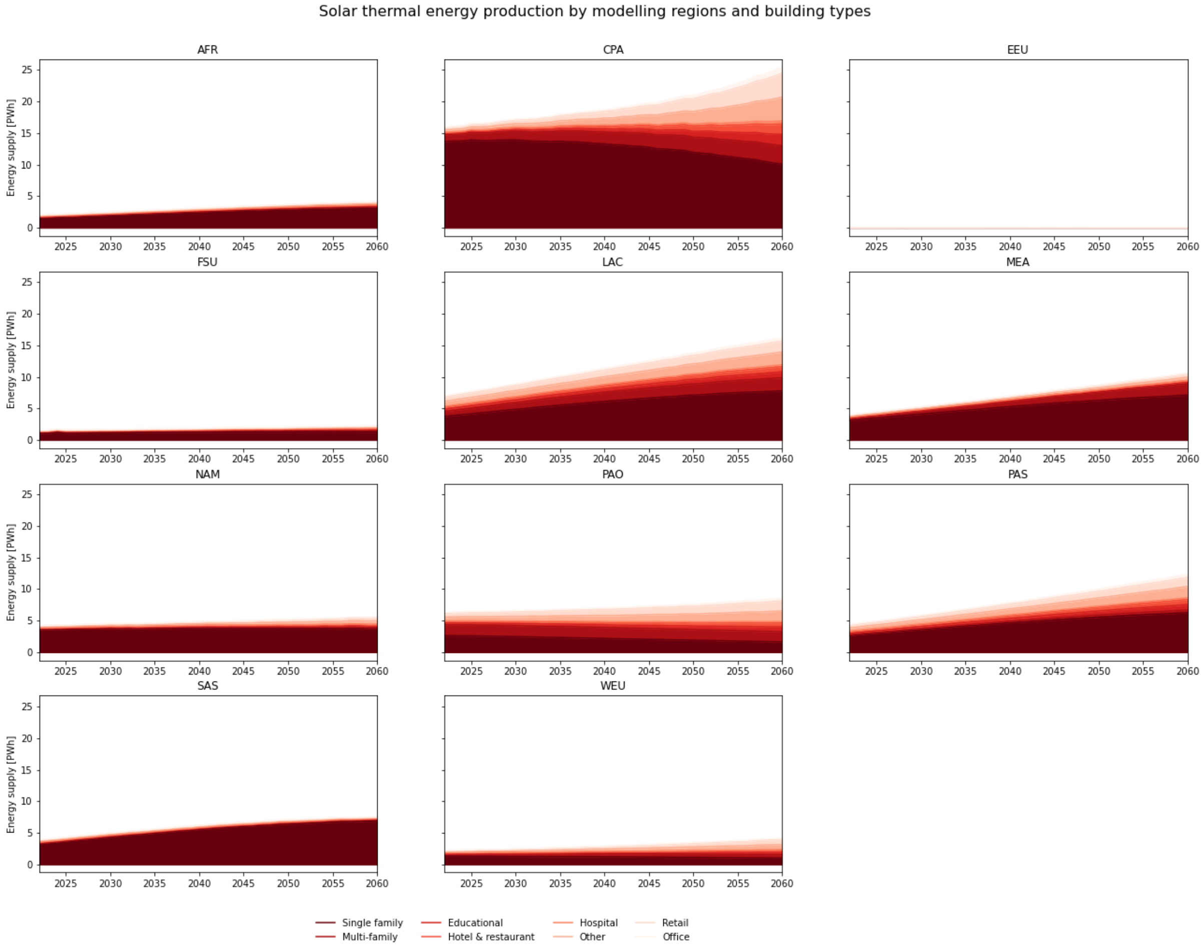


Figure 61. Projected changes of technical potential for solar thermal energy supply in different regions and building types between 2022 and 2060.

During the analysis period, the technical potential of total PV/T energy production (the sum electric and thermal yield; $E_{PV/T\ total\ supp}$) was predicted to increase for every building types. It can summarized based on the Figure 62 that PV/T collectors can generate the largest total energy output for the single family buildings (about 50% share). The share of multifamily and commercial/public buildings in the $E_{PV/T\ total\ supp}$ is 31% and 19% in the first year of the analysis period.

Because of the highest absolute and relative values of $RA_{PV/T\ syst}$, Centrally Planned Asia and North America have the top modeled $E_{PV/T\ total\ supp}$ at single family buildings in 2022 (Figure 62). For this reason, the Centrally Planned Asia region's dominance is also seen in other building types (multifamily: 3.5 PWh and commercial/public: 3.4 PWh), too. The second maximum local production over rooftops of multifamily buildings was anticipated in the Pacific OECD. After Centrally Planned Asia, the simulated $E_{PV/T\ total\ supp}$ values for commercial/public buildings indicates minor differences among the regions, with $E_{PV/T\ total\ supp}$ of about 2 PWh (Latin America: 2.3; Pacific OECD: 1.8; North America: 1.5 PWh).

Over the simulated period, $E_{PV/T\ total\ supp}$ is characterized by decline for several building types within specific regions. More precisely, this negative trend is specifically linked to single family and multifamily houses. While the share of multifamily buildings falls only in the Pacific OECD, the tendencies for the single family houses can be split by economic status of the given region. There is an obvious rising potential in the developed regions (e.g., North America, Pacific OECD, Western Europe and Eastern Europe) and in Centrally Planned Asia, but the $E_{PV/T\ total\ supp}$ is expected to climb in such regions as Latin America, Middle East Africa and South Asia. In case of commercial/public buildings, the year-to-year increase of the $E_{PV/T\ total\ supp}$ is observable in each geographical area (Figure 62).

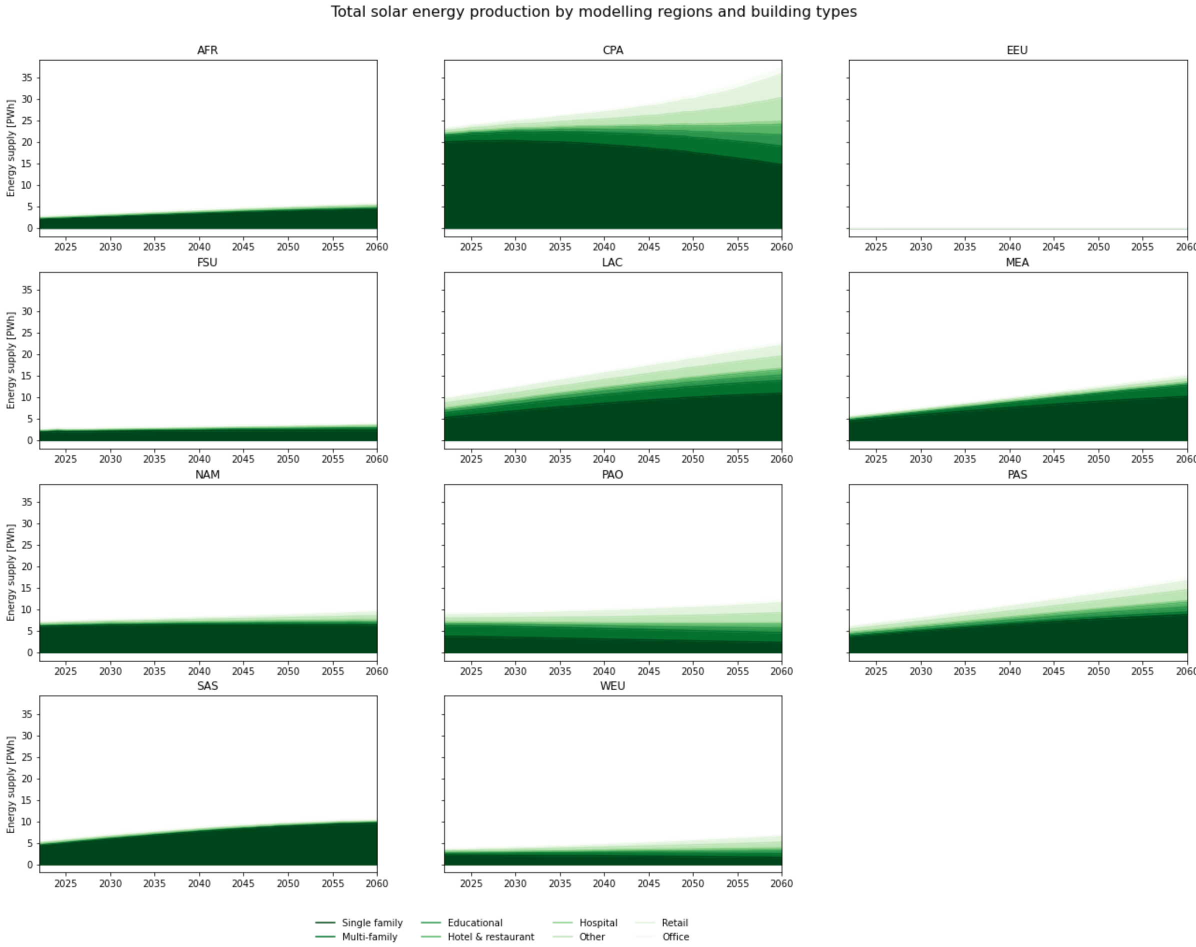


Figure 62. Projected changes of technical potential for building-integrated total solar energy supply by regions and building types between 2022 and 2060.

Figure 63 shows how much solar energy can be produced on building roofs by extrapolating the historical expansion of installed solar system's capacity. Since such data is available especially for PV panels, the presented results focus on exploring a possible on-site energy production could be achieved by applying PV panels (see the technical description in Table 7) instead of PV/T collectors. Since it can be expected that the skyrocketing of the utilization of PV technology will continue in the next decades, the current building related electricity consumption (≈ 16 PWh in 2019) can potentially be covered by 2032 around globally. Nevertheless, as the latest crisis in global supply chain emphasized, there could be major uncertainties of what fraction of the estimated supply potential will be realized in the future. Other uncertainty factor is that there could be different utilization levels on regional level, which may result in different dynamics as compared to the estimated magnitudes.

By 2060, the BISE model with the Deep utilization scenario estimates the global rooftop PV electricity generation to be 121 PWh (Figure 63), which is more than 7 times larger than the actual building-related consumption. The largest growth was modelled for the period between 2035 and 2048, which is supported by two factors in the model. First, as it was presented earlier, the physically suitable rooftop area is anticipated to expand as new buildings are introduced to the building stock. Secondly, the new buildings are built with the need for installing PV panels on their rooftops. In the Deep utilization scenario, PV panels could be utilized in all buildings, if the current trend will continue and the manufacturing will have the capacity to cover the needs. As a result, the largest PV electricity generation may be reached in Centrally Planned Asia (33.52 PWh), Latin America (17.86 PWh) and Middle East Africa (12.61 PWh), depending on such uncertainty factors as level of incentives, availability of manufacturing material, preference of solar PVs over other high energy-efficiency technologies as well as the development of the electricity grid and energy storage techniques.

In the Baseline case, the estimated rooftop PV potential was found to be 59% lower by 2060 globally (Figure 63; Table 13). This is related to the different utilization dynamics and target level being considered in the two assumptions. If all physically suitable rooftop areas of buildings are covered by PV panels, it would theoretically be possible to immediately balance the building-related electricity consumption. However, if only the physically suitable areas are utilized, there could a lock-in effect in the system. Thanks to the rapid progress of the solar technology, it becomes technologically possible to mitigate the reduction in the energy production by partially shaded cells (e.g., applying different topologies; Alves et al., 2021). For this reason, it seems to be increasingly reasonable to utilize PV panels in physically less suitable rooftop areas, which may help to decrease the lock-in effect. In addition to that, as van de Ven et al. (2021) pointed out, replacing land-based PV panels by rooftop installed systems could alleviate the competition for land resources.

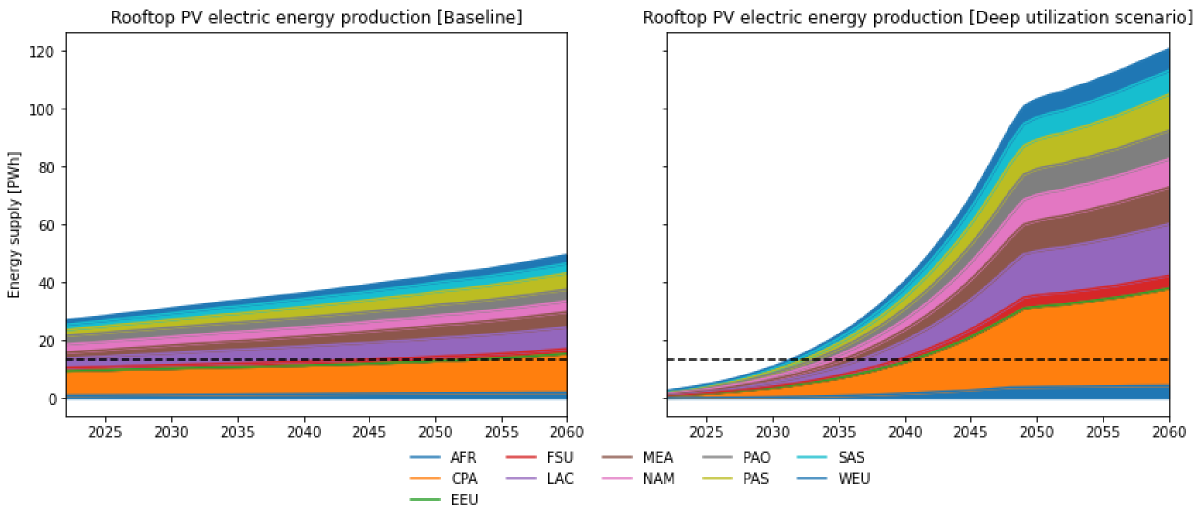


Figure 63. Baseline and scenario-based projection of technical rooftop PV energy supply between 2022 and 2060. The dashed lines indicate the level of global building electricity consumption in 2019.

Table 13. Comparison of the technical potential of rooftop PV electricity simulated by the baseline and deep utilization cases.

Scenario	Baseline			Deep utilization		
	2022 PWh	2060 PWh	Δ% to 2022	2022 PWh	2060 PWh	Δ% to Baseline
CPA	8.29	13.50	+61%	0.84	33.52	+148%
LAC	3.25	7.48	+130%	0.33	17.86	+139%
NAM	2.82	3.79	+34%	0.28	9.80	+159%
PAO	3.03	4.03	+33%	0.30	9.85	+144%
WEU	1.57	2.89	+84	0.16	7.45	+158%
World	26.93	49.49	+84%	2.69	120.58	+146%

4.2.3. Estimating intra-annual building solar energy supply

In order to understand the inter-annual changes of the rooftop PV/T energy supply, it also is essential to have a better insight on the intra-annual variations. Since the roof space was assumed to vary on year-to-year basis in the BISE model, so that the intra-annual distribution of the solar energy production is governed by the solar climate of a given region.

It can be concluded, therefore, that the shapes of the representative curves for the $E_{TH\ output}$ and $E_{EL\ output}$ are in a robust connection with the annual magnitudes of the solar irradiation (Figure 64). For the annual variability of the $E_{TH\ output}$, the maxima are outlined in South Asia (146.7 kWh/m^2) and Pacific OECD (156.9 kWh/m^2) regions. The simulated $E_{TH\ output}$ curves, except for the MEA and SAS regions, possess two peaks over the typical year. In the African and Pacific Asian regions, for example, the highest $E_{TH\ output}$ can be identified during the solar equinoxes (i.e., end of March and September). In Latin America and PAO, on the other hand, this was estimated to be rather in late December/early January. In the mid-latitude regions, the maxima occur in May and September, as vertically-elongated clouds filter the sunlight frequently during the summer months. Presumably the opposite results in the single-peaked summertime maximum in the Middle East and Africa. In the South Asia, the monsoon period leads to this characteristic shape of the curves.

In general, the regional differences in the inter-annual variability of $E_{TH\ output}$ is proportional to the number of seasons. Hence, considerable variability is outlined for the regions with four seasons (Centrally Planned Asia: 96.6 kWh/m^2; North America (91.8 kWh/m^2), while the lowest was simulated for the regions with no significant seasonality (Pacific Asia: 15.9 kWh/m^2; AFR: 13.3 kWh/m^2).

The maxima (FSU: 78.6 and NAM: 77.3 kWh/m^2) and annual differences (6.7–59.2 kWh/m^2) of the $E_{EL\ output}$ was estimated to be lower related to the $E_{TH\ output}$ (Figure 64). It is also a noticeable characteristic that the difference between the two types of energy productions could be smallest in the regions of Former Soviet Union, North America, Eastern and Western Europe, primarily during wintertime days with clear sky.

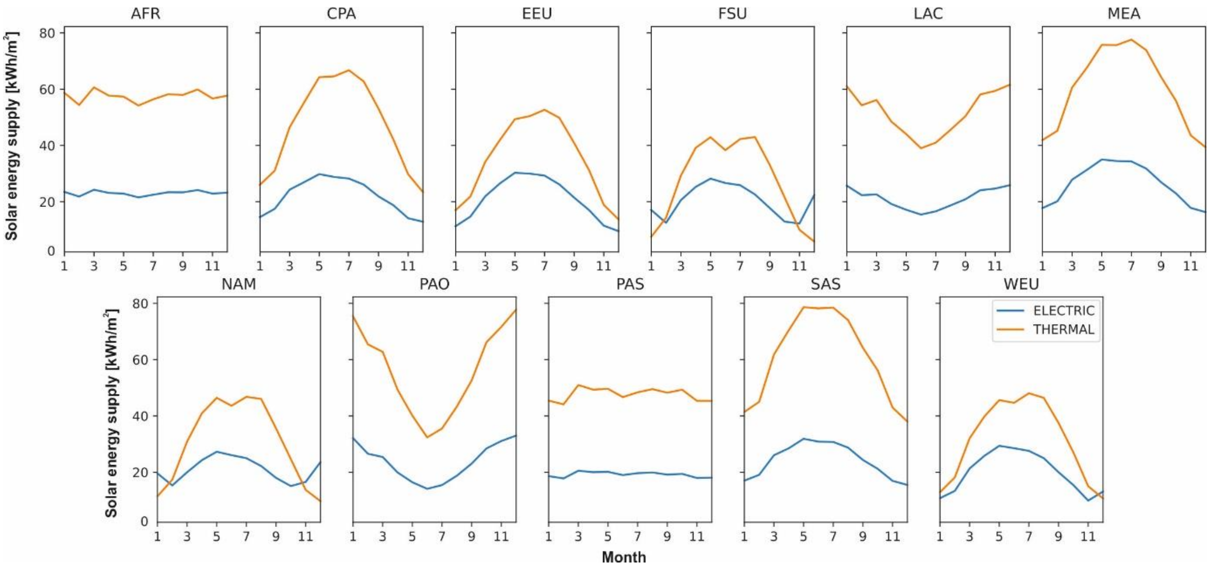


Figure 64. Estimated mean monthly variability of PV/T technical potential by solar electric (blue curves) and thermal (red curves) energy production [in kWh/m^2] in different regions over the analyzed period.

As the radiation income and thus the energy generation can have well observable daily course, which determines how much solar on-site energy can utilized, stored, fed into the grid, we estimated the regional curves for two, astronomically opposite days (e.g., winter solstice – 21th December; summer solstice – 21th July) in a typical modeling year (Figure 65 and Figure 66). Overall, the daily dynamics of the $E_{TH\ output}$ are undoubtedly much more intense related to that of the $E_{EL\ output}$, which is manifested in a rapid uptake (declining) period during the local morning (afternoon). It also seems to be a general feature that in areas where the proportion of direct radiation is higher on a given day (i.e., in the summer months, around the local noon or during clear-sky periods), the surface temperature of the PV/T collector could have 'hot spots' and thus more thermal energy (more $E_{TH\ output}$) is streamed through fluid of the system. On the other hand, where the radiation is more scattered and attenuated (i.e., higher latitudes and winter months), the magnitude of $E_{TH\ output}$ is smaller, and then the $E_{EL\ output}$ becomes increasingly important in relative sense.

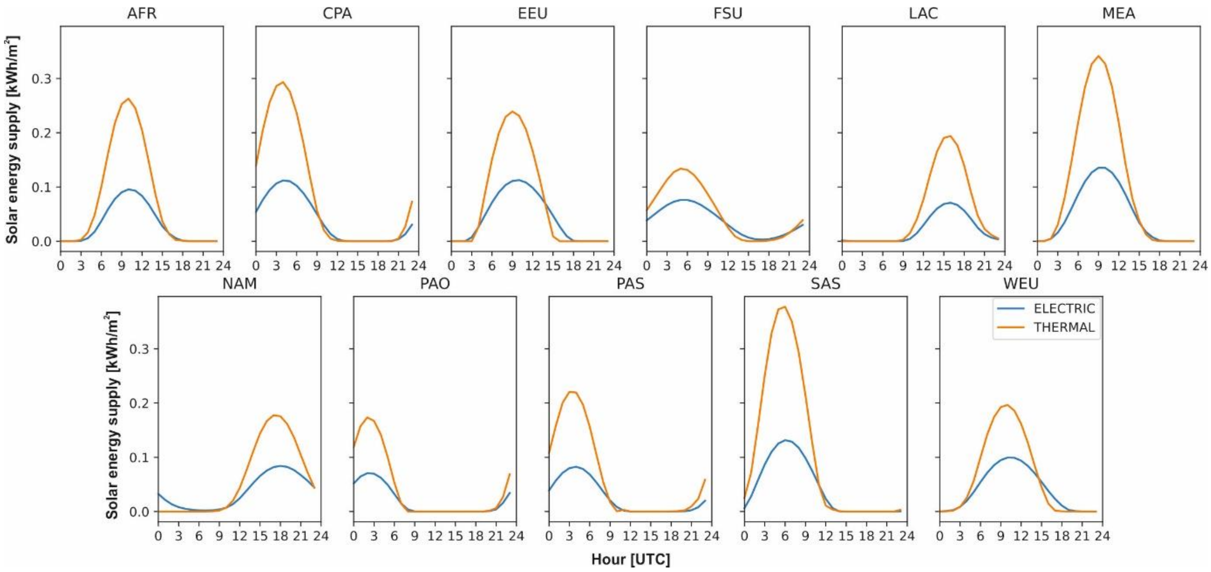


Figure 65. Estimated mean hourly variability of PV/T technical potential by solar electric (blue curves) and thermal (red curves) energy production [in kWh/m^2] in different regions during the summer solstice (2060).

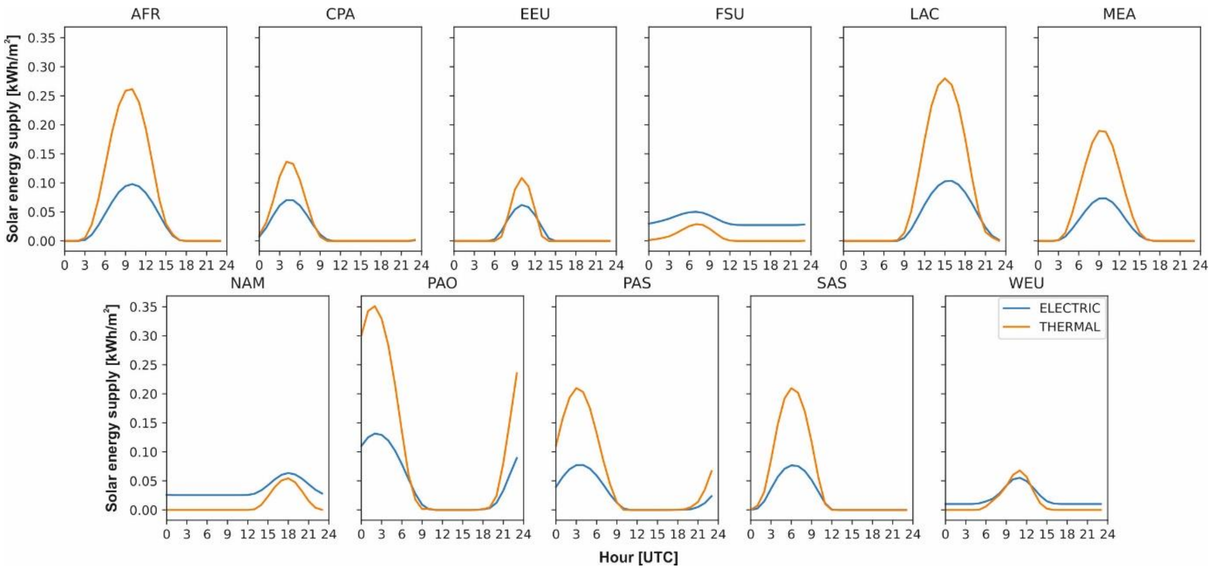


Figure 66. Estimated mean hourly variability of PV/T technical potential by solar electric (blue curves) and thermal (red curves) energy production [in kWh/m^2] in different regions during the winter solstice (2060).

In the Section 4.3., we present addition solar energy curves using the hourly outputs of the BISE model. Nevertheless, it is important to note that the $E_{EL\ output}$ will be the output of energy generation by PV panels. Moreover, the energy production will be analyzed not on 1 m^2 of the rooftop but 1 m^2 of the floor area of buildings (i.e., in W/m^2 useful floor area dimension).

4.2.4. Verification of the BISE model

Roof area: According to our analysis, the total roof was estimated to be about 220 billion m^2 and around its one third can be suitable for solar energy harness with PV/T collectors. In general, the roof area availability was found to be largest in the most urbanized areas (e.g., Centrally Planned Asia and North America) where the building stock is well extended. The dynamics of the (total and available) roof area was relied on the reference roof area data (i.e., the one derived from geospatial sources) as well as estimations from the 3CSEP-HEB model. Since the projection of these socio-economic parameters has its methodological limitations, the estimated shares of residential and tertiary rooftops include certain uncertainties.

Although the validation of our results for the total and available roof area cannot be complete (e.g., very different regions of interest), the related magnitudes seem to be in line with other references from the literature. For the European Union, for instance, Bódis et al. (2019) found the $RA_{PV/T\ syst}$ to be around 7935 million m_2. This value is slightly larger than that of the sum in the BISE for the WEU and EEU regions (5632 million m^2). Because of the similarities of the methodologies, this could be the consequence of the different threshold value applied for the building raster layers. By using finer resolution LIDAR data for the US, Margolis et al. (2017) estimated a useful area on the rooftops to be 4922 million m^2. Although the North American region also includes Canada in the BISE, the $RA_{PV/T\ syst}$ was projected to be 4795 m^2 in our analysis, indicating also some underestimation. For China, on the other hand, we found a larger value as compared to that published in the study of Grau et al. (2012). Therefore, no clear tendency of over- and underestimation is outlined based on this constrained comparison.

Solar rooftop PV/T energy supply: Since there are no estimations of PV/T energy production on global scale to best of the authors' knowledge, we can only validate the modeled $E_{EL\ total\ supp}$ values against the results of global and regional studies designed for quantifying the technical potential of rooftop PV panels. The simulated technical potentials of the corresponding electricity generation in the reviewed investigations seem to be fairly diverse, having a range between 6 (Hoogwijk, 2004) to 27.51 PWh (Joshi et al., 2021). Therefore, the 18.04 PWh of electric output given by the upgraded BISE model is in the upper end of this scale.

The differences among the results are presumably related to the dissimilar target periods, rooftop area approaches and technological measures. Since the technology of the solar panels has improved drastically in the recent years, the earlier studies projected the lowest energy supply, due to the lower electric efficiencies and nominal powers of their hypothesized system. In Hoogwijk (2004), for example, the η_{EL} was set to 14%, which has been remarkably exceeded over the years by the current state-of-the-art PV panels. Another explanation for the lower $E_{EL\ total\ supp}$ values in Hofman et al. (2002) and Hoogwijk (2004) may stem from the preference of less accurate empirical (or statistical) assumptions for the RA_{total} in contrast with more reliable GIS-based methods. On the other hand, it is a common feature of the reviewed modelling assessments that they all calculated the largest technical potentials for the North American (e.g., USA), East Asian (e.g., China) and European (e.g., Germany) countries.

If the simulation of the upgraded BISE model and the one of the most recent global study (Joshi et al., 2021) is compared, it can be concluded that they predicted around 9.5 PWh larger values for the $E_{EL\ total\ supp}$ than that of in our analysis. This 52% difference, however, is attributed to that Joshi et al. (2021) hypothesized the U_F to be 1 (all rooftop area is covered with solar systems), while we considered values between 0.28 and 0.33 for this variable. Nevertheless, they offset the high $RA_{PV/T\ syst}$ with very low η_{EL} (Joshi et al., 2021: 10%; this study: 21.6%). Despite the different GIS approach employed in their analysis for deriving building geometry (i.e., machine learning method based on road length, population, built-up area boundaries and building footprint), the estimated RA_{total} values indicate a great agreement (Joshi et al., 2021: 193 875 km^2; this study: 217 187 km^2). It underlines, therefore, the essence of the choice of the U_F in shaping the final result for the $E_{EL\ total\ supp}$.

4.3. Analyzing the energy balance

The climate neutral or net zero buildings or building self-sufficiency refer to the fact that energy demand is at least equal to or less than the solar electric generation in a given point of the year. The potential of buildings to become self-sufficient or net-zero depends on two aspects; 1) reducing energy demand, and 2) renewable energy produced in the building to satisfy energy demand. Each of the regions has different renewable energy production potential as per geographical location, season, and time of the year/month/day. Thus, we compare solar electric production with end-use service energy demand on a monthly and hourly scale to provide a holistic assessment on the building self-sufficiency principals. In the section, total thermal energy demand is compared with total solar electric and solar thermal energy generation for the period between 2022 and 2060 for all 11 regions across the globe. The total energy is calculated by adding two key findings namely total energy demand for heating and cooling, and hot water from the HEB model. The solar electric and solar thermal energy generation findings for each of regions are used from BISE model. Together with total energy use and total energy produced data are presented for each of the regions to showcase the energy balance of the building sector in different regions. To have a consistent comparison of the demand and supply side, the respective values are computed for 1 m^2 of the floor area of the total building sector.

By comparing the modelled values of the specific building energy demand and PV electricity production in 2022 on global level, there are two separate periods of the year during which the energy budged has different sign (Figure 67). From late October to February, the demand values are higher than the solar energy supply, meaning that the energy consumption does not seem to be fully covered by solar energy sources. This can be explained with that vast majority of buildings are located in the Northern Hemisphere, and during these months the solar radiation income has the intra-annual minimum in this period of the year. Simultaneously, the demand for space heating is very high, which was modelled to be the most crucial among the energy end-uses (Figure 42). Also, it is important to note that this study only refers to the solar electric production to show the net zero potential. This relies on the assumption that a low energy demand on the building-side will be achieved through a wide-spread penetration of heat-pumps. Since heat pumps work with electricity, the local electric production can be directly used for both heating and cooling purposes.

From middle of February to late October, the PV electricity generation may cover the demand from all end-uses. In fact, after a transition period, the solar energy supply was simulated to be about 2.5 times higher relative to the demand side from middle of March to September (Figure 67). Furthermore, the global data also shows that if best practices for construction and renovation are adopted then only building sector will achieve self-sufficiency in most of the time in a year. If the present policies and trend continues then energy demand of the building sector would be much higher in most of the year than the onsite production.

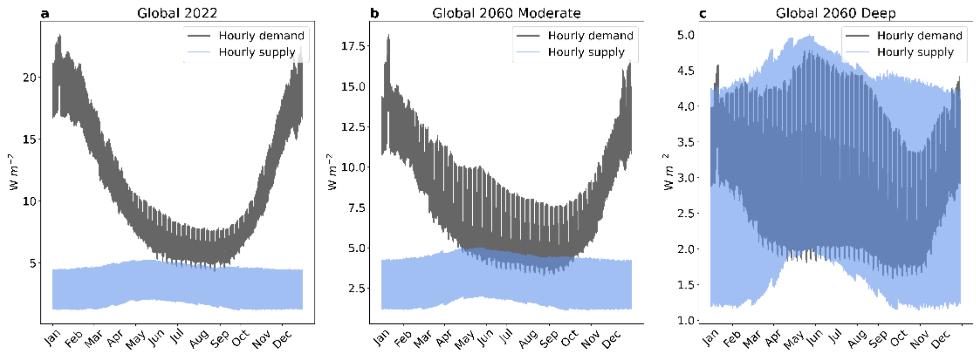


Figure 67. The comparison of hourly specific energy demand for space heating, cooling and hot water production and PV electric energy supply on global level in 2022 (a) and in 2060 (b – Moderate; c – Deep).

Figure 68 below presents all hourly regional energy balance cases. Similar trends with respective to the policies can be observed in the regional data than in the global figures. More precisely, we can observe that if best practices are adopted in every region, then only buildings can achieve self-sufficiency. However, in different regions in different time of the year, it could be the case that despite adopting best practices, building self-sufficiency may not be achieved in certain time of the year.

It is also observable that although it is likely to achieve self-sufficiency by 2060, if we look into regions-specific results, we will see that there are regions such as Centrally Planned Asia or Eastern Europe where it is not possible to achieve self-sufficiency throughout the year. In these regions, from late October to February, energy demand of the building is higher than on-site energy production. In Eastern Europe and Centrally Planned Asia, for example, this high demand mostly results from space heating. However, regions like Latin America, Middle East and Africa, Africa, Western Europe, Pacific OECD, and Pacific Asia, building self-sufficiency is possible to achieve throughout the year.

Regions such as Latin America, Middle East and Africa, Pacific OECD, and Pacific Asia can achieve net zero from the beginning of the modelling period due to their immense potential of producing solar energy. Precisely, these regions have an apt climatic potential (e.g., low latitude + moderate radiation extinction by cloud particles) which enables these regions to harness solar energy in a very large extent. However, this statement assumes, that energy can be redistributed within the entire region and within the years perfectly. This might be a case if the electricity grid has been improved significantly and is well connected (for the spatial redistribution), and if electricity storage potential has been increased (for the temporal redistribution). For the rest of the regions, the net zero or climate neutrality can be achieved only with reducing the energy demand substantially over the years. To shed more light on the climatic impact, we present also the energy balance analysis for different climate zones.

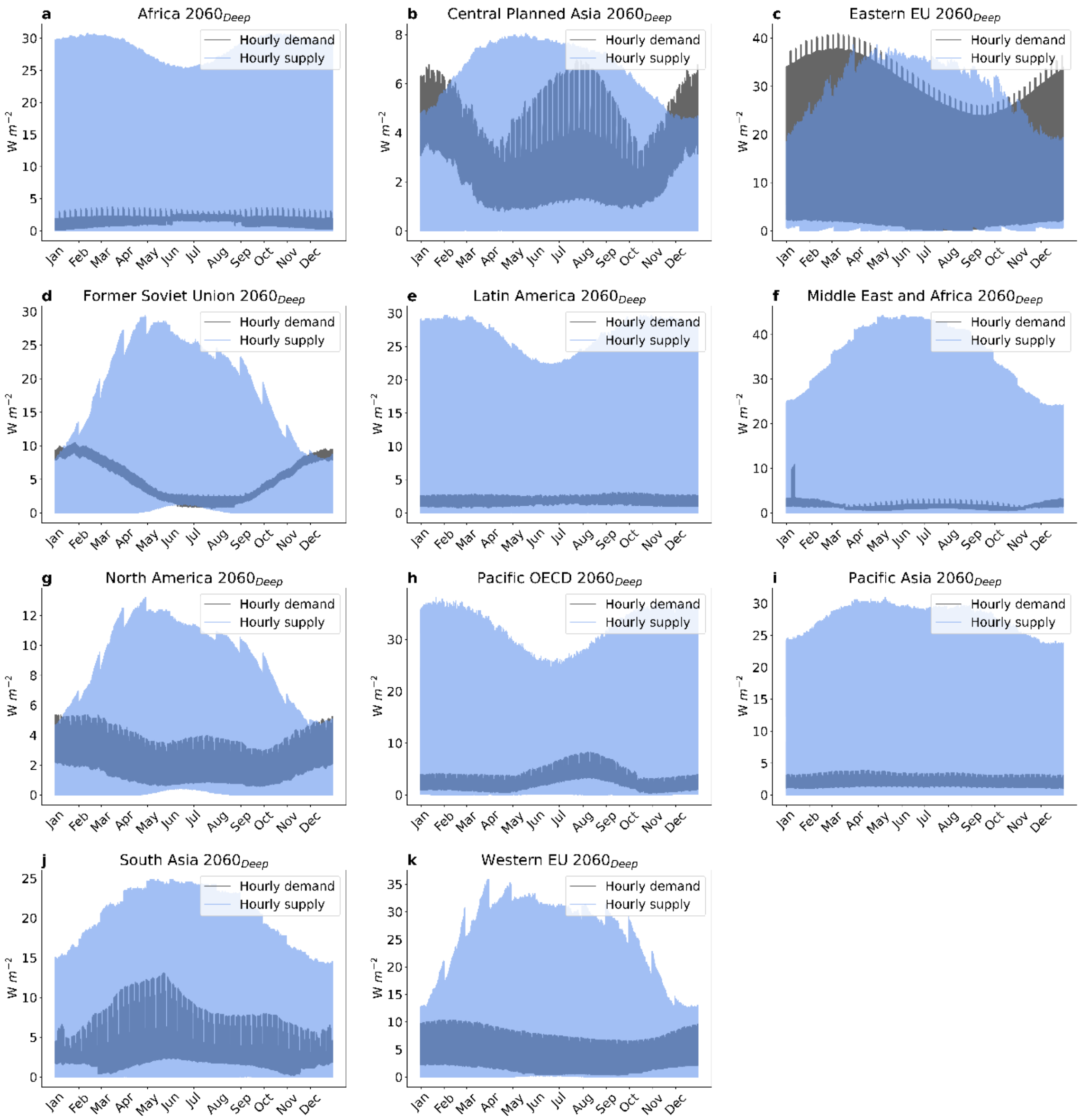


Figure 68. The comparison of hourly specific energy demand for space heating, cooling and hot water production and PV in different key regions by 2060 (Deep Efficiency scenario).

Figure 69 below presents the climate zone specific data. It can be generally underlined that climate zones with heating requirement is often unable to achieve building self-sufficiency. One of the key reasons for not achieving self-sufficiency in developing nations are the low reduction in energy demand. In HEB model, we assume that only after 2037, the new building contractions will be using the state-of-the-art technologies, and thus, the energy demand reduction in these regions are low compared to the regions in global south. The figures in different climate zones thus put more emphasis on the urgency of taking up best practices even in the developing nations to achieve net zero energy status. Therefore, combining the HEB model with the BISE solar energy supply model could create a powerful tool that not only makes aware of the future tendencies of energy demand in the building sector but also informs on how the demand side could be balanced using an abundant and carbon neutral energy source.

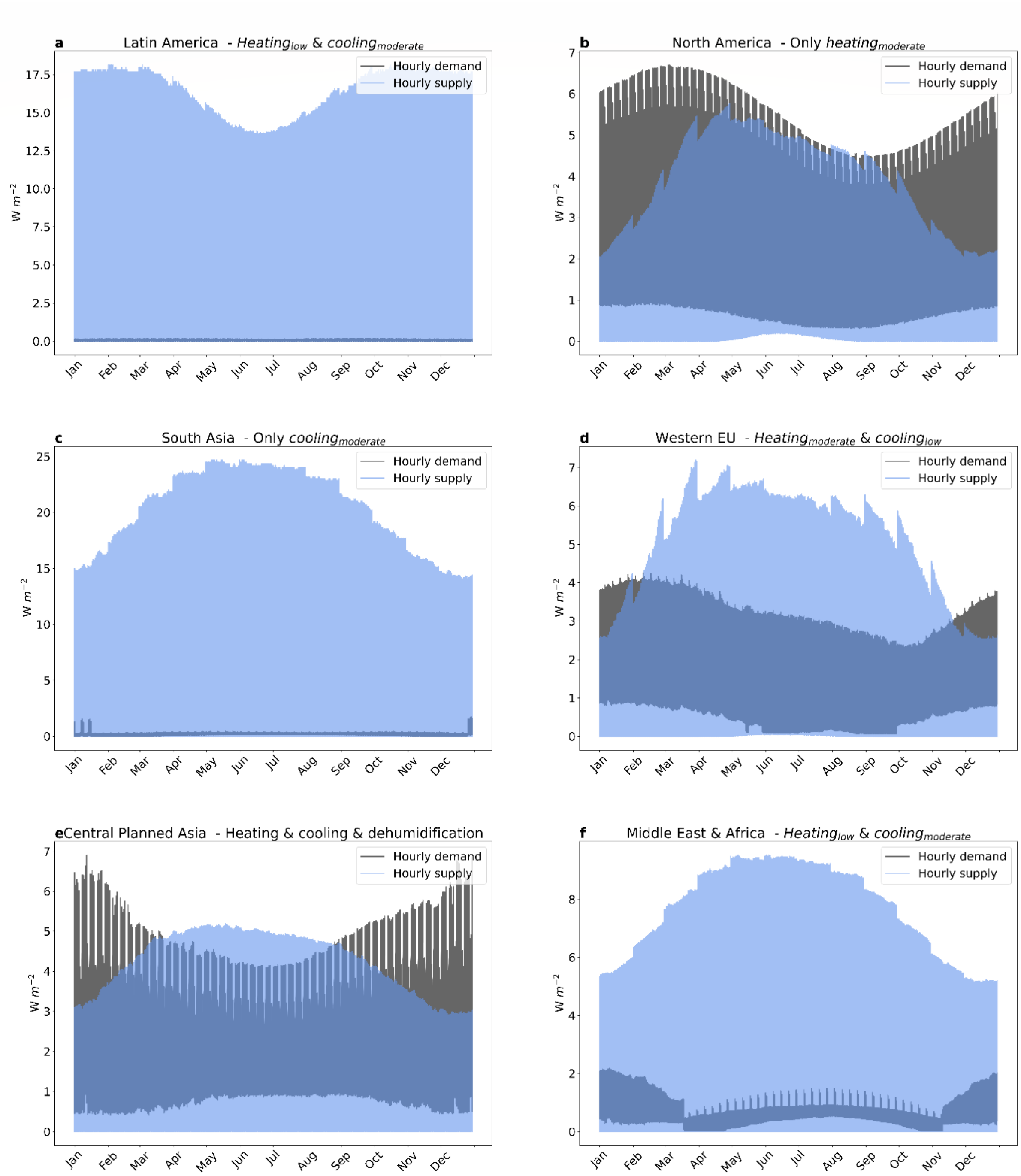


Figure 69. The comparison of hourly specific energy demand for space heating, cooling and hot water production and PV in different key regions and climate zones by 2060 (Deep Efficiency scenario).

5. Conclusion and policy recommendations

This study demonstrates the potential of self-sufficiency of the building sector by assessing the annual and hourly energy demand and supply profiles of the building sector. The findings of the study show that with state-of-the-art high-efficiency buildings implemented worldwide, it is possible to achieve self-sufficiency in the future. However, this pathway towards high-efficiency or net-zero is ambitious in its assumptions and requires strong policy support. On the contrary, if policy support to implement more high-efficiency buildings is not in place (Frozen Efficiency scenario) or even the present policy scenarios are continued (Moderate Efficiency scenario), then the total thermal energy demand of the building sector could increase to 30-80% by 2060 compared to the 2022 level.

The Deep-efficiency and Net-zero scenarios clearly indicate that each region has the capacity to substantially reduce energy demand over time. The Moderate and Frozen efficiency scenarios, on the other hand, show that if the rate of retrofit remains moderate and the share of advanced new buildings does not increase significantly over time, the building sector's total energy demand will almost certainly result in significant energy consumption and CO_2 emissions. As a result, bold and ambitious policies are required to achieve the enormous potential of the construction sector. Furthermore, the findings of the study also show that onsite production capacity of the buildings can be used to meet the total energy demand, and it is even possible to achieve climate neutrality status or self-sufficiency status. However, climate neutrality or self-sufficiency in buildings can only be achieved if service energy demand of the building end uses is substantially reduced. Irrespective of the regions and climate zones, this argument holds valid. Therefore, to promote best practices and state of the art high-efficiency buildings, the following recommendations can be explored:

1. In developed countries, the building energy demand can be met by executing an advanced retrofit of existing and historic buildings. To encourage advanced retrofit, ambitious building codes and standards must be implemented and enforced properly. Positive incentives, including as subsidies and tax breaks, can be given to both the developer and the owner to effectively reinforce the advance retrofit. If retrofits cannot be done in advance, world energy consumption will rise in tandem with the growth in floor area, and energy demand will be unable to be reduced significantly over time due to significant carbon lock-in. In order to achieve a low-energy building stock, the study found that rigorous policy acts in building energy efficiency measures, as well as their timely execution, are even more crucial than an increased retrofit rate.
2. In developing regions, new building stock plays a significant role in reducing energy demand; as a result, the construction of new energy-efficient buildings should adhere to a strict building code that requires new construction to meet a high degree of energy performance. In order to attain suitable high-efficiency constructions, building certification and labeling, technological transfer, training of building specialists, and financial incentives should all be considered.
3. The findings of the study show that single family households have the highest potential to generate solar energy and hence, separate building codes and energy performance standards need to be in place for single family household to ensure PV/T installation and high efficiency standards.
4. As the findings of the BISE model show, the solar energy producible on building rooftops varies depending on climate zones, so it would be prudent to provide positive incentives to install high-efficiency PV/T systems in cooling-dominated climate zones, as buildings in cooling-dominated climates require significant cooling energy. In mid-latitudes with temperate

climates, where the technical potential for thermal energy production is less obvious, PV panels are suggested since they provide more electric energy, are less expensive, and are more widely accepted than PV/T systems.

Despite a significant reduction in energy demand and an increase in energy generation from building integrated PV/T, it is possible that the 1.5 degree goals may not be met. In other words, despite a worldwide shift to very energy efficient buildings, the building sector will still fall short of meeting climate change mitigation targets because other factors (such as climatic factors, economic uncertainties, and behavioral changes) influence both demand and supply in the sector. As a result, lowering building energy consumption requires decarbonization of energy supply as well as considerable behavioral and lifestyle adjustments. A large spread of renewable energy technology appears to be necessary to decarbonize electricity supply. Behavioral and lifestyle changes can aid in limiting floor area expansion, avoiding excessive energy usage, and improving the efficiency of building energy systems.

References

Aisa, A., Iqbal, T., 2016. Modelling and simulation of a solar water heating system with thermal storage. 7th IEEE Annu. Inf. Technol. Electron. Mob. Commun. Conf. IEEE IEMCON 2016. https://doi.org/10.1109/IEMCON.2016.7746283

Allan, J., Bansard, J., Jones, N., Luomi, M., Tan, J.M., Sun, Y., 2021. Glasgow Climate Change Conference: 31 October – 13 November 2021. Earth Negot. Bull. 12, 1–40.

Alves, T., Torres, J.P.N., Marques Lameirinhas, R.A., Fernandes, C.A.F., 2021. Different techniques to mitigate partial shading in photovoltaic panels. Energies 14. https://doi.org/10.3390/en14133863

Anderson, T.N., Duke, M., Morrison, G.L., Carson, J.K., 2009. Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector. Sol. Energy 83, 445–455. https://doi.org/10.1016/j.solener.2008.08.013

ASHRAE, 2015. Heating, Ventilating, and Air-Conditioning APPLICATIONS.

Bódis, K., Kougias, I., Jäger-Waldau, A., Taylor, N., Szabó, S., 2019. A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union. Renew. Sustain. Energy Rev. 114, 109309. https://doi.org/10.1016/j.rser.2019.109309

Boermans, T., Bettgenhäuser, K., Offermann, M., Schimschar, S., 2012. Renovation tracks for Europe Up to 2050. Building renovation in Europe- what are the choices? 52.

BP Energy outlook, 2021. Statistical Review of World Energy globally consistent data on world energy markets . and authoritative publications in the field of energy. BP Energy Outlook 2021 70, 8–20.

Burch, J., Christensen, C., 2007. Towards development of an algorithm for mains water temperature. Am. Sol. Energy Soc. - Sol. 2007 36th ASES Annu. Conf., 32nd Natl. Passiv. Sol. Conf., 2nd Renew. Energy Policy Mark. Conf. Sustain. Energy Puts Am. to Work 1, 173–178.

Byrne, J., Taminiau, J., Kurdgelashvili, L., Kim, K.N., 2015. A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of Seoul. Renew. Sustain. Energy Rev. 41, 830–844. https://doi.org/10.1016/j.rser.2014.08.023

Capros, P., Zazias, G., Evangelopoulou, S., Kannavou, M., Fotiou, T., Siskos, P., De Vita, A., Sakellaris, K., 2019. Energy-system modelling of the EU strategy towards climate-neutrality. Energy Policy 134, 110960. https://doi.org/10.1016/j.enpol.2019.110960

Capstick, S., Lorenzoni, I., Corner, A., Whitmarsh, L., 2014. Prospects for radical emissions reduction through behavior and lifestyle change. Carbon Manag. 5, 429–444. https://doi.org/10.1080/17583004.2015.1020011

Ciancio, V., Salata, F., Falasca, S., Curci, G., Golasi, I., 2020. Energy demands of buildings in the framework of climate change : An investigation across Europe. Sustain. Cities Soc. 60, 102213. https://doi.org/10.1016/j.scs.2020.102213

CIESIN, 2018. Gridded population of the world (GPW), v4. National identifier grid. Country-level information and sources revision 11. [WWW Document]. URL https://sedac.ciesin.columbia.edu/binaries/web/sedac/collections/gpw-v4/gpw-v4-country-level-summary-rev11.xlsx

Corbane, C., Syrris, V., Sabo, F., Politis, P., Melchiorri, M., Pesaresi, M., Soille, P., Kemper, T., 2021.

Convolutional neural networks for global human settlements mapping from Sentinel-2 satellite imagery. Neural Comput. Appl. 33, 6697–6720. https://doi.org/10.1007/s00521-020-05449-7

Czétány, L., Vámos, V., Horváth, M., Szalay, Z., Mota-Babiloni, A., Deme-Bélafi, Z., Csoknyai, T., 2021. Development of electricity consumption profiles of residential buildings based on smart meter data clustering. Energy Build. 252. https://doi.org/10.1016/j.enbuild.2021.111376

De Soto, W., Klein, S.A., Beckman, W.A., 2006. Improvement and validation of a model for photovoltaic array performance. Sol. Energy 80, 78–88. https://doi.org/10.1016/j.solener.2005.06.010

Delbeke, J., Runge-Metzger, A., Slingenberg, Y., Werksman, J., 2019. The paris agreement. Towar. a Clim. Eur. Curbing Trend 24–45. https://doi.org/10.4324/9789276082569-2

DISER, 2020. National Greenhouse Accounts Factors October 2020 1–84.

Diwania, S., Agrawal, S., Siddiqui, A.S., Singh, S., 2020. Photovoltaic–thermal (PV/T) technology: a comprehensive review on applications and its advancement. Int. J. Energy Environ. Eng. 11, 33–54. https://doi.org/10.1007/s40095-019-00327-y

Dotzauer, E., 2002. Simple model for prediction of loads in district - heating systems. Appl. Energy 73, 277–284. https://doi.org/10.1016/S0306-2619(02)00078-8

DUALSUN, 2021. Datasheet SPRING 375 Shingle Black. [WWW Document]. URL https://my.dualsun.com/wp-content/uploads/sites/2/DualSun-EN-Datasheet-SPRING-375-Shingle-Black.pdf (accessed 2.13.21).

Duffie, J.A., Beckman, W.A., 1982. Solar engineering of thermal processes, Design Studies. https://doi.org/10.1016/0142-694x(82)90016-3

Erbs, D.G., Klein, S.A., Duffie, J.A., 1982. Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. Sol. Energy 28, 293–302. https://doi.org/10.1016/0038-092X(82)90302-4

Fuentes, E., Arce, L., Salom, J., 2018. A review of domestic hot water consumption profiles for application in systems and buildings energy performance analysis. Renew. Sustain. Energy Rev. 81, 1530–1547. https://doi.org/10.1016/j.rser.2017.05.229

Gelaro, R., McCarty, W., Suárez, M.J., Todling, R., Molod, A., Takacs, L., Randles, C.A., Darmenov, A., Bosilovich, M.G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A.M., Gu, W., Kim, G.K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J.E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S.D., Sienkiewicz, M., Zhao, B., 2017. The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). J. Clim. 30, 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Grau, T., Huo, M., Neuhoff, K., 2012. Survey of photovoltaic industry and policy in Germany and China. Energy Policy 51, 20–37. https://doi.org/10.1016/j.enpol.2012.03.082

Hendron, R., Anderson, R., Christensen, C., Eastment, M., Reeves, P., 2004. Development of an Energy Savings Benchmark for All Residential End-Uses. SimBuild 2004 1–8.

Henning, H.M., Palzer, A., 2014. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies - Part I: Methodology. Renew. Sustain. Energy Rev. 30, 1003–1018. https://doi.org/10.1016/j.rser.2013.09.012

Hofman, Y., de Jager, D., Molenbroek, E., Schilig, F., Voogt, M., 2002. The potential of solar electricity to reduce CO2 emissions. Utrecht, Ecofys 106.

Homerenergy, 2021. HOMER Grid 1.8 - User Guide. [WWW Document]. URL https://www.homerenergy.com/products/grid/docs/latest/index.html (accessed 1.11.21).

Hoogwijk, M.M., 2004. On the global and regional potential of renewable energy sources, Assembly.

IEA, 2021a. Key World Energy Statistics 2021 1–82.

IEA, 2021b. Net Zero by 2050: A Roadmap for the Global Energy Sector. Int. Energy Agency 224.

IEA, 2020. Global Energy Review 2019. Glob. Energy Rev. 2019. https://doi.org/10.1787/90c8c125-en

INSPIRE, 2020. INSPIRE GEOPORTAL. Data sets by Theme and Cadastral parcels. [WWW Document]. URL https://inspire-geoportal.ec.europa.eu/overview.html?view=themeOverview&theme=cp (accessed 12.29.20).

Jacobson, M.Z., Jadhav, V., 2018. World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. Sol. Energy 169, 55–66. https://doi.org/10.1016/j.solener.2018.04.030

Joshi, S., Mittal, S., Holloway, P., Shukla, P.R., Ó Gallachóir, B., Glynn, J., 2021. High resolution global spatiotemporal assessment of rooftop solar photovoltaics potential for renewable electricity generation. Nat. Commun. 12, 1–15. https://doi.org/10.1038/s41467-021-25720-2

Knobloch, F., Pollitt, H., Chewpreecha, U., Lewney, R., Huijbregts, M.A.J., Mercure, J.F., 2021. FTT:Heat — A simulation model for technological change in the European residential heating sector. Energy Policy 153, 112249. https://doi.org/10.1016/j.enpol.2021.112249

Kranzl, L., Aichinger, E., Büchele, R., Forthuber, S., Hartner, M., Müller, A., Toleikyte, A., 2019. Are scenarios of energy demand in the building stock in line with Paris targets? Energy Effic. 12, 225–243. https://doi.org/10.1007/s12053-018-9701-1

Kurdgelashvili, L., Li, J., Shih, C.H., Attia, B., 2016. Estimating technical potential for rooftop photovoltaics in California, Arizona and New Jersey. Renew. Energy 95, 286–302. https://doi.org/10.1016/j.renene.2016.03.105

Levesque, A., Pietzcker, R.C., Baumstark, L., De Stercke, S., Grübler, A., Luderer, G., 2018. How much energy will buildings consume in 2100? A global perspective within a scenario framework. Energy 148, 514–527. https://doi.org/10.1016/j.energy.2018.01.139

Li, W., Zhou, Y., Cetin, K., Eom, J., Wang, Y., Chen, G., Zhang, X., 2017. Modeling urban building energy use: A review of modeling approaches and procedures. Energy 141, 2445–2457. https://doi.org/10.1016/j.energy.2017.11.071

Lindberg, K.B., Bakker, S.J., Sartori, I., 2019. Modelling electric and heat load profiles of non-residential buildings for use in long-term aggregate load forecasts. Util. Policy 58, 63–88. https://doi.org/10.1016/j.jup.2019.03.004

Macêdo, W.N., Zilles, R., 2007. Operational results of grid-connected photovoltaic system with different Inverter's Sizing Factors (ISF). Prog. Photovoltaics Res. Appl. 15, 337–352. https://doi.org/10.1002/pip.740

Mainzer, K., Killinger, S., McKenna, R., Fichtner, W., 2017. Assessment of rooftop photovoltaic potentials at the urban level using publicly available geodata and image recognition techniques. Sol. Energy 155, 561–573. https://doi.org/10.1016/j.solener.2017.06.065

Majid, Z.A.A., Razak, A.A., Ruslan, M.H., Sopian, K., 2015. Characteristics of solar thermal absorber materials for cross absorber design in solar air collector. Int. J. Automot. Mech. Eng. 11, 2582–2590. https://doi.org/10.15282/ijame.11.2015.36.0217

Mangiante, M.J., Whung, P.Y., Zhou, L., Porter, R., Cepada, A., Campirano, E., Licon, D., Lawrence, R., Torres, M., 2020. Economic and technical assessment of rooftop solar photovoltaic potential in Brownsville, Texas, U.S.A. Comput. Environ. Urban Syst. 80, 101450. https://doi.org/10.1016/j.compenvurbsys.2019.101450

Margolis, R., Gagnon, P., Melius, J., Phillips, C., Elmore, R., 2017. Using GIS-based methods and lidar data to estimate rooftop solar technical potential in US cities. Environ. Res. Lett. 12. https://doi.org/10.1088/1748-9326/aa7225

Masson-Delmotte, V., P., Zhai, A., Pirani, S.L., Connors, C., Péan, S., Berger, N., Caud, Y., Chen, L., Goldfarb, M.I., Gomis, M., Huang, K., Leitzell, E., Lonnoy, J.B.R., Matthews, T.K., Maycock, T., Waterfield, O., Yelekçi, R., Yu, and B.Z., 2021. The Physical Science Basis. Contribution of Working Group I to the 552 Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Glob. Warm. 1.5°C. An IPCC Spec. Rep. impacts Glob. Warm. 1.5°C above pre-industrial levels Relat. Glob. Greenh. gas Emiss. pathways, Context Strength. Glob. response to Threat Clim. Chang. 2021, 1–2.

Mastrucci, A., van Ruijven, B., Byers, E., Poblete-Cazenave, M., Pachauri, S., 2021. Global scenarios of residential heating and cooling energy demand and CO2 emissions. Clim. Change 168, 1–26. https://doi.org/10.1007/s10584-021-03229-3

Matthes, F.C., Hermann, H., Zimmer, W., 2017. The Vision Scenario for the European Union 2017 Update for the EU-27 49, 65.

Matuska, T., Zmrhal, V., Metzger, J., 2009. Detailed modeling of solar flat-plate collectors with design tool kolektor 2.2. IBPSA 2009 - Int. Build. Perform. Simul. Assoc. 2009 2289–2296.

Mutschler, R., Rüdisüli, M., Heer, P., Eggimann, S., 2021. Benchmarking cooling and heating energy demands considering climate change, population growth and cooling device uptake. Appl. Energy 288, 116636. https://doi.org/10.1016/j.apenergy.2021.116636

Nägeli, C., Jakob, M., Catenazzi, G., Ostermeyer, Y., 2020. Towards agent-based building stock modeling: Bottom-up modeling of long-term stock dynamics affecting the energy and climate impact of building stocks. Energy Build. 211. https://doi.org/10.1016/j.enbuild.2020.109763

Netherlands Enterprise Agency, 2020. The Netherlands : list of fuels and standard CO 2 emission factors version of January 2020 Colophon.

Ó Broin, E., Mata, É., Göransson, A., Johnsson, F., 2013. The effect of improved efficiency on energy savings in EU-27 buildings. Energy 57, 134–148. https://doi.org/10.1016/j.energy.2013.01.016

Palzer, A., Henning, H.M., 2014. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies - Part II: Results. Renew. Sustain. Energy Rev. 30, 1019–1034. https://doi.org/10.1016/j.rser.2013.11.032

Pedersen, L., Stang, J., Ulseth, R., 2008. Load prediction method for heat and electricity demand in buildings for the purpose of planning for mixed energy distribution systems. Energy Build. 40, 1124–1134. https://doi.org/10.1016/j.enbuild.2007.10.014

Perez, R., Ineichen, P., Seals, R., Michalsky, J., Stewart, R., 1990. Modeling daylight availability and irradiance components from direct and global irradiance. Sol. Energy 44, 271–289.

https://doi.org/10.1016/0038-092X(90)90055-H

Petrichenko, K., 2014. Net-Zero Energy Buildings: Global and Regional Perspectives. Central European University.

Pokorny, N., Matuška, T., 2020. Glazed photovoltaic-thermal (PVT) collectors for domestic hotwater preparation in multifamily building. Sustain. 12. https://doi.org/10.3390/su12156071

Preisler, T., Dethlefs, T., Renz, W., Dochev, I., Seller, H., Peters, I., 2017. Towards an agent-based simulation of building stock development for the city of hamburg. Proc. 2017 Fed. Conf. Comput. Sci. Inf. Syst. FedCSIS 2017 11, 317–326. https://doi.org/10.15439/2017F271

RETScreen, 2020. Clean energy project analysis: RETScreen® engineering & cases textbook: natural resources Canada.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Chang. 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Ringkjøb, H.-K., Haugan, P.M., Solbrekke, I.M., 2018. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew. Sustain. Energy Rev. 96, 440–459. https://doi.org/10.1016/j.rser.2018.08.002

Romero Rodríguez, L., Duminil, E., Sánchez Ramos, J., Eicker, U., 2017. Assessment of the photovoltaic potential at urban level based on 3D city models: A case study and new methodological approach. Sol. Energy 146, 264–275. https://doi.org/10.1016/j.solener.2017.02.043

Roscini, A.V., Rapf, O., Kockat, J., 2020. Contributions from the building sector to a strengthened 2030 climate target - On the way to a CLIMATE-NEUTRAL EUROPE 2030 24.

Sachs, J., Moya, D., Giarola, S., Hawkes, A., 2019. Clustered spatially and temporally resolved global heat and cooling energy demand in the residential sector. Appl. Energy 250, 48–62. https://doi.org/10.1016/j.apenergy.2019.05.011

Sadeqi, A., Tabari, H., Dinpashoh, Y., 2022. Spatio-temporal analysis of heating and cooling degree-days over Iran. Stoch. Environ. Res. Risk Assess. 36, 869–891. https://doi.org/10.1007/s00477-021-02064-3

Santamouris, M., Vasilakopoulou, K., 2021. Present and Future Energy Consumption of Buildings: Challenges and Opportunities towards Decarbonisation. e-Prime 1, 100002. https://doi.org/10.1016/j.prime.2021.100002

Schulzweida, U., 2019. CDO User Guide 1–206.

Schupfner, M., Wieners, K.-H., Wachsmann, F., Steger, C., Bittner, M., Jungclaus, J., Früh, B., Pankatz, K., Giorgetta, M., Reick, C., Legutke, S., Esch, M., Gayler, V., Haak, H., de Vrese, P., Raddatz, T., Mauritsen, T., von Storch, J.-S., Behrens, J., Brovkin, V., Claussen, M., Crueger, T., Fast, I., Fiedler, S., Hagemann, S., Hohenegger, C., Jahns, T., Kloster, S., Kinne, S., Lasslop, G., Kornblueh, L., Marotzke, J., Matei, D., Meraner, K., Mikolajewicz, U., Modali, K., Müller, W., Nabel, J., Notz, D., Peters-von Gehlen, K., Pincus, R., Pohlmann, H., Pongratz, J., Rast, S., Schmidt, H., Schnur, R., Schulzweida, U., Six, K., Stevens, B., Voigt, A., Roeckner, E., 2019. DKRZ MPI-ESM1.2-HR model output prepared for CMIP6 ScenarioMIP. https://doi.org/10.22033/ESGF/CMIP6.2450

Shukla, A.K., Sudhakar, K., Baredar, P., 2017. Renewable energy resources in South Asian countries: Challenges, policy and recommendations. Resour. Technol. 3, 342–346. https://doi.org/10.1016/j.reffit.2016.12.003

SolarPower Europe, 2019. Global Market Outlook for Solar Power / 2019-2023.

SUNPOWER, 2021. Maxeon 3 400W - Residential AU.

Tracker, C.A., 2021. COP26 Glasgow sectoral initiatives currently.

TRIPLE SOLAR, 2021. Triple Solar Heat Pump Panels. [WWW Document]. URL https://triplesolar.eu/wp-content/uploads/2021/10/Triple-Solar-product-information-PVT-heat-pump-panels-M3-2021.pdf (accessed 2.13.21).

UNEP, 2019. 2019 Global Status Report for Buildings and Construction Sector | UNEP - UN Environment Programme, United Nations Environment Programme.

Urge-vorsatz, D., 2012. Best Practice Policies for Low Carbon & Energy Buildings Best Practice Policies for Low Carbon & Energy Buildings.

Urge-Vorsatz, D., Khosla, R., Bernhardt, R., Chan, Y.C., Verez, D., Hu, S., Cabeza, L.F., 2020. Advances toward a net-zero global building sector. Annu. Rev. Environ. Resour. 45, 227–269. https://doi.org/10.1146/annurev-environ-012420-045843

Urge-Vorsatz, D., Petrichenko, K., Antal, M., Staniec, M., Labelle, M., Ozden, E., Labzina, E., 2012. Best Practice Policies for Low Energy and Carbon Buildings: A Scenario Analysis.

van de Ven, D.J., Capellan-Peréz, I., Arto, I., Cazcarro, I., de Castro, C., Patel, P., Gonzalez-Eguino, M., 2021. The potential land requirements and related land use change emissions of solar energy. Sci. Rep. 11, 1–12. https://doi.org/10.1038/s41598-021-82042-5

van Ruijven, B.J., De Cian, E., Sue Wing, I., 2019. Amplification of future energy demand growth due to climate change. Nat. Commun. 10, 1–12. https://doi.org/10.1038/s41467-019-10399-3

Werner, S., 2017. International review of district heating and cooling. Energy 137, 617–631. https://doi.org/10.1016/j.energy.2017.04.045

Wiginton, L.K., Nguyen, H.T., Pearce, J.M., 2010. Quantifying rooftop solar photovoltaic potential for regional renewable energy policy. Comput. Environ. Urban Syst. 34, 345–357. https://doi.org/10.1016/j.compenvurbsys.2010.01.001

Wolf, S., Teitge, J., Mielke, J., Schütze, F., Jaeger, C., 2021. The European Green Deal — More Than Climate Neutrality. Intereconomics 56, 99–107. https://doi.org/10.1007/s10272-021-0963-z

Yang, D., Ye, Z., Nobre, A.M., Du, H., Walsh, W.M., Lim, L.I., Reindl, T., 2014. Bidirectional irradiance transposition based on the Perez model. Sol. Energy 110, 768–780. https://doi.org/10.1016/j.solener.2014.10.006

Zondag, H.A., De Vries, D.W., Van Helden, W.G.J., Van Zolingen, R.J.C., Van Steenhoven, A.A., 2002. The thermal and electrical yield of a PV-thermal collector. Sol. Energy 72, 113–128. https://doi.org/10.1016/S0038-092X(01)00094-9

Technology datasets for modeling the energy demand of data centers

Eric Masanet* and Thomas Wheeler

Bren School of Environmental Science and Management, University of California, Santa Barbara

* emasanet@ucsb.edu

Contents

Introduction 2

Approach 3

Reviews of reported data 4

Operator data 5

National data center energy statistics 7

Technology datasets and model structure 8

Infrastructure equipment energy use 8

Network devices 11

Storage Devices 11

Servers 13

Market Segmentation and Regionalization 15

Projecting Future Energy Demand 15

References 17

Introduction

Digitalization holds promise for reducing societal demand for energy across major end use sectors (IEA 2017; Wilson et al. 2020). All digitally-enabled services rely on internet infrastructure, which is broadly divisible into two macro-level technology segments: (1) data centers that facilitate data processing, storage, and computations; and (2) data communication networks that send information between data centers and connected end user devices via (often combinations of) wired and wireless networks (Masanet et al. 2020; Aslan et al. 2018).

For digitally-enabled services to contribute to a low energy-demand future, it is important that they robustly deliver economy-level energy savings. More precisely, digitally-enabled services are most beneficial from an energy perspective when a net negative balance exists between: (1) the combined energy demand of the internet infrastructure and the connected devices necessary to provide the service, and (2) the energy savings enabled by the service across applicable end use sector(s). Ideally, this net balance would be calculated using a life-cycle energy accounting perspective on both sides of the equation to account for both direct and indirect energy use effects (Horner et al. 2016).

As digitalization proliferates, it will be important for both energy analysts and policymakers to understand the scales and drivers of this balance moving forward. However, to date the major integrated assessment models (IAMs) and energy systems models (ESMs) used to analyze low energy-demand pathways lack explicit representation of data centers and data networks in their modeling structures. These modeling gaps preclude endogenous calculations of net systems-level energy balances.

In this project, we take a first step toward addressing these modeling gaps by compiling public technology datasets and assembling an efficient modeling structure for quantifying the direct energy requirements of data centers. The datasets and framework can be applied to different world regions on the basis of installed technology stocks and their energy use characteristics. In the future, the framework can be expanded to further include data networks and, owing to the bottom-up nature of the approach, to incorporate the broader life-cycle energy demands associated with the installed technology stocks.

The datasets and modeling structure—which are contained in a separate Excel workbook—are described in the remainder of this report. Furthermore, to conclude this report, we comment on methods used for projecting future data center energy demand for consideration in IAMs and ESMs.

Approach

This project compiled datasets that are compatible with a bottom-up approach to modeling data center energy demand at the regional level. The general bottom-up structure employed in our proposed modeling framework is depicted in Figure 1. We chose the bottom-up methodology given the richness of its technology-level parameters compared to other data center energy modeling methods, notably top-down and extrapolation-based approaches. The tradeoffs associated with each modeling method are briefly summarized in Table 1, based on a methods review conducted as part of this project.

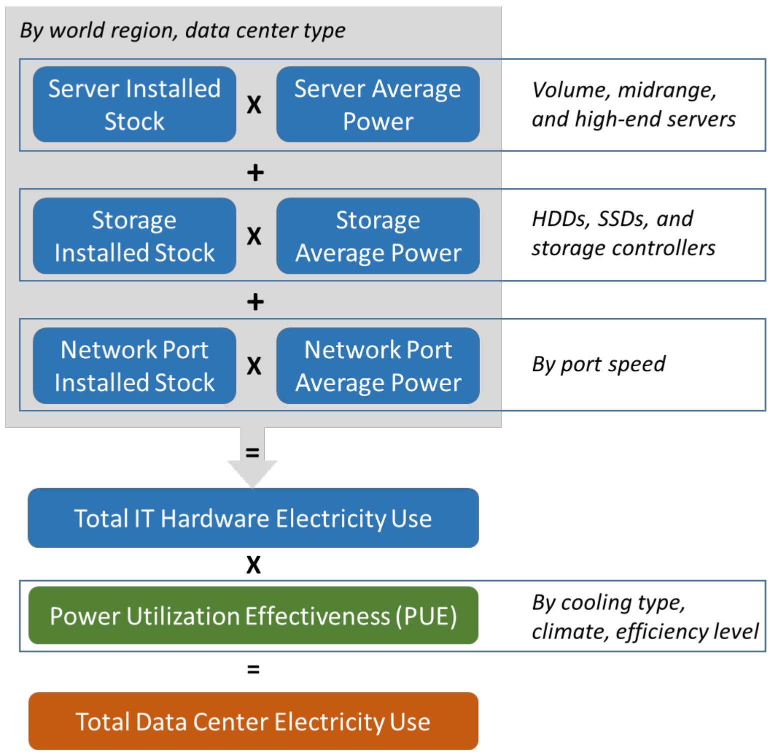


Figure 1: Bottom-up modeling structure employed in this project

Due to its parameter richness and explanatory power, bottom-up models have historically been the method of choice for investigating technology and structural drivers of data center energy use at national and global scales (Brown et al. 2007; Koomey 2008, 2011; Hintemann and Clausen 2016; Shehabi et al. 2016; Montevecchi et al. 2020; Masanet et al. 2020; Schneider Electric 2021).

However, as noted in Table 1, the explanatory power of bottom-up models comes at the expense of being quite data intensive. Extensive data requirements can pose a barrier to using bottom-up methods outside of select modeling teams that have already invested in data collection, which can often involve the purchase of proprietary market analysis firm datasets that cannot be shared (see e.g., Shehabi et al. 2016).

To minimize data barriers, we focused solely on compiling data gleaned from publicly-available data sources, including data and assumptions contained in previously-published bottom-up studies and public information from market analysis firms. Data sources for each aspect of the model (infrastructure, servers, storage, and network devices) are described in relevant sections below.

We further note that we exclude cryptocurrency mining centers from our framework, given fundamental differences in IT hardware and operating characteristics compared to conventional data centers. We refer the reader to Lei et al. (2021) for an overview of modeling approaches for blockchain technologies, and to the Cambridge Bitcoin Energy Consumption Index (https://ccaf.io/cbeci/) for estimates on Bitcoin mining in particular.

Table 1: Comparison of different data center energy use estimation approaches

Method	Advantages	Disadvantages

Bottom-up	• Based on detailed technology-level analysis
	• Can capture technology over time
	• Substantial explanatory power
	• Useful for exploring savings potentials of efficiency improvements and market structural shifts
		• Substantial data requirements
		• Resource and time intensive
		• Often requires proprietary market analyst data
		    • Costly
		    • Can't be shared
		• Different (often non-public) data sources lead to different results
		• Infrequently conducted

Top-down and extrapolation-based	• Generally anchored in more detailed bottom-up estimates • Few variables = minimal data requirements • Fast and easy to generate • Useful for exploring high-level "what if" scenarios for broad trends	• Lack of technology and structural detail = lack of explanatory power and risk of missing major shifts • Small errors can compound over long projection periods • Risk of misinterpretation

Reviews of reported data

Ideally, sector energy models should be validated against collected data or official energy statistics to ensure that their results are reasonably accurate. Therefore, this project conducted a brief review of reported data center energy statistics to establish whether sufficient information exists to validate the results of our proposed modeling framework.

We focused on two possible categories of reported data: (1) energy data reported by data center operators; and (2) data center energy statistics collected at the national level in different countries. While we found evidence of reported data in both categories, the comprehensiveness, transparency, and utility of reported data to date fall far short of what is needed to fully validate data center energy models at regional or global levels. Our findings are summarized below. We stress that a key priority for improved models should be the initiation of large-scale data collection efforts by national governments, or other independent parties (e.g., industry associations), to compile and publish statistics on data center energy use for different data center types.

Operator data

There are many thousands of data center operators globally. For the purposes of this project, we divided operators into three broad categories: (1) internet-related service companies whose primary businesses rely on data center operations, (2) data center infrastructure companies, and (3) on-premises operators.

The first category includes many of the world's largest technology companies, such as Google, Microsoft, Amazon, Facebook, Apple, and IBM. These companies operate large stand-alone hyperscale and cloud-service data centers around the world. The second category refers to companies that provide outsourced data center infrastructure services, inclusive of colocation data centers operated by companies like Digital Realty, Equinix, and NTT, who also operate many large data centers globally. The third category is comprised of onsite data centers operated by all other firms, many of which can be much smaller data centers falling into the midsize, server room, and server closet categories (Ganeshalingam et al. 2017) and which typically occupy space within multi-use buildings across all economic sectors.

While the vast majority of data center operators fall into the third category, recent research suggests that the largest shares of overall energy use have shifted—or will soon shift—to the (far fewer and much larger) data centers operated by companies falling into the first two categories (Cisco 2018; Masanet et al. 2020; Montevecchi et al. 2020). Therefore, we focused our review on key technology and data center infrastructure companies to determine if their reported data could be useful for aspects of model validation. This focus was also motivated by the acknowledgement that on-premises operator reporting is likely rare.

Figure 2 summarizes results for select large data center operators that report electricity use via corporate sustainability reports, annual reports, and/or their websites. We focused on reported electricity use values given that, excepting occasional direct fuel use in backup generators, data centers run exclusively on electricity. Several problems were observed when interpreting the collected data.

First, few operators currently report electricity use for their data center operations (indicated with a single asterisk in Figure 2). Most often, operators report total company-wide electricity use, which encompasses all aspects of their operations (data centers, office buildings, lab spaces, etc.) (indicated with a double asterisk in Figure 2). For companies that mostly operate data centers (e.g., Google, colocation providers), company-wide electricity use may be reasonably interpreted as an upper bound on their data center electricity use. However, for other companies with expansive non data-center operations, such upper bound approximations are less reliable. For example, Amazon operates hundreds of Whole Foods grocery stores and e-commerce distribution centers in addition to their data centers, and China Telecom operates vast data communication networks in addition to data centers.

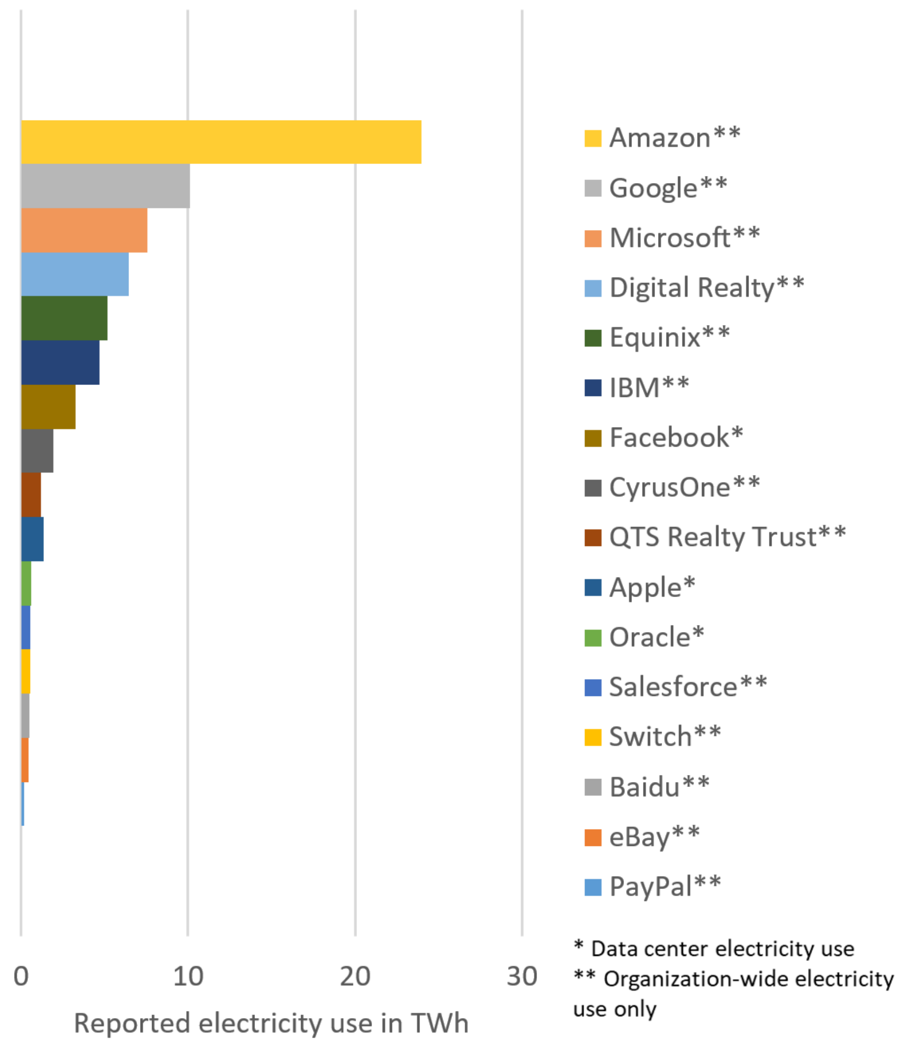


Figure 2: Reported electricity use values of select technology companies. Note: all data are for 2018, except for Amazon, which first reported electricity use in 2020

Second, some companies include leased colocation data center operations in their reported electricity use totals (e.g., Apple). While this is positive from a transparency perspective, it presents a risk of double counting the same electricity use also reported by colocation companies. Third, at least one company (Tencent) only reported electricity use for their operations in China, whereas they also operate many other data centers globally.

Therefore, our review concluded that operator reported data are currently of limited use for validating data center energy models at the regional or national scales. Their utility may improve in the future as more operators publicly report their energy data. Ideally, operators would report the electricity use of their data centers explicitly, inclusive of the names of colocation providers associated with any reported electricity use for leased data centers. Furthermore, as more operators report within our first two categories, validation may become increasingly possible for specific market segments (e.g., hyperscale and cloud data centers) that have direct correspondence to those categories.

National data center energy statistics

Our review revealed that there are very few efforts at the national level to compile and report energy statistics for data centers.

In the United States, the quadrennial Commercial Building Energy Consumption Survey (CBECS) has compiled information on the numbers and typical server quantities associated with on-premises data centers with buildings classified by principal building activity (e.g., office, retail, education, etc.) (U.S. EIA 2022). While these data have been used by energy analysts to estimate the numbers and energy use of midsize and small data centers in the United States (Ganeshalingam et al. 2017), CBECS does not compile energy use values for these on-premises data centers.

A pilot program to include buildings dedicated to data centers—which would capture most data centers within our first two operator categories—was conducted by CBECS staff in 2018 (U.S. EIA 2021). However, due to lack of adequate responses by operators of these data centers, the CBECS staff concluded that extending the survey to dedicated data center buildings faced too many participation/data quality barriers to move forward using existing CBECS approaches.

In China, where the data center sector is growing faster than anywhere else in the world, the national government compiles statistics on the power utilization effectiveness (PUE) and the design number of IT racks installed in hyperscale and large data centers (NDCADG 2020). These data have also been used by energy researchers to derive estimates of data center energy use in China (Greenpeace East Asia 2019). However, like the U.S. CBECS, statistics on the energy use of reporting data centers are not available.

Lastly, we identified three national efforts in Europe that compile energy statistics for data centers. In the Netherlands, the national statistics bureau Statistics Netherlands has been collecting electricity use data for around 200 data centers since 2017. The latest available statistics indicated 2020 electricity use of around 3.2 TWh among 205 reporting data centers; however, it is unclear whether smaller on-premises data centers operated by non-technology organizations are included in the dataset (CBS 2022).

In the UK, the technology trade association TechUK organizes the Climate Change Agreement (CCA) for Data Centres, which includes reporting of energy use by data center companies. Recent public CCA data indicate that 129 reporting facilities consumed around 2.6 TWh in 2016; with the latest values reported by TechUK indicating energy consumption of around 2.9 TWh for commercial and colocation data centers (TechUK 2017, 2020). The dataset excludes on-premises data centers operated by non-technology organizations (TechUK 2020).

Thus, while our review found evidence of national-level statistics on data center energy use, global coverage is still far less than needed for validation of global energy use estimates. Within the few individual countries that collect data, such data may prove useful for validating modeled estimates of the market segments that are within their scopes.

Technology datasets and model structure

As shown in Figure 1, our proposed model framework is comprised of four computational segments, each of which is supported by best-available technology datasets that were compiled during this project. The datasets and model computations are contained in an Excel spreadsheet that accompanies this report. The Excel spreadsheets enables the quantification of regional data center energy use estimates by choosing the appropriate regional data sources and specifying key input variable assumptions. In the sections below, we briefly describe the approach and key data sources that are associated with each computational segment. The reader is advised to refer to the project Excel spreadsheet for further details as indicated in each section.

Infrastructure equipment energy use

Figure 3 depicts the major energy-consuming technologies associated with data centers, inclusive of backup power generators that may be used intermittently due to grid outages (Brown et al. 2007). Within the data center itself, all current technologies run exclusively on electricity. The technologies needed for reliable power provision (switch gear, uninterruptible power supplies, and power distribution units), data center space conditioning (cooling and humidification systems), and general tasks (lighting, office space) are often collectively referred to as "infrastructure equipment" (Brown et al. 2007; Shehabi et al. 2016).

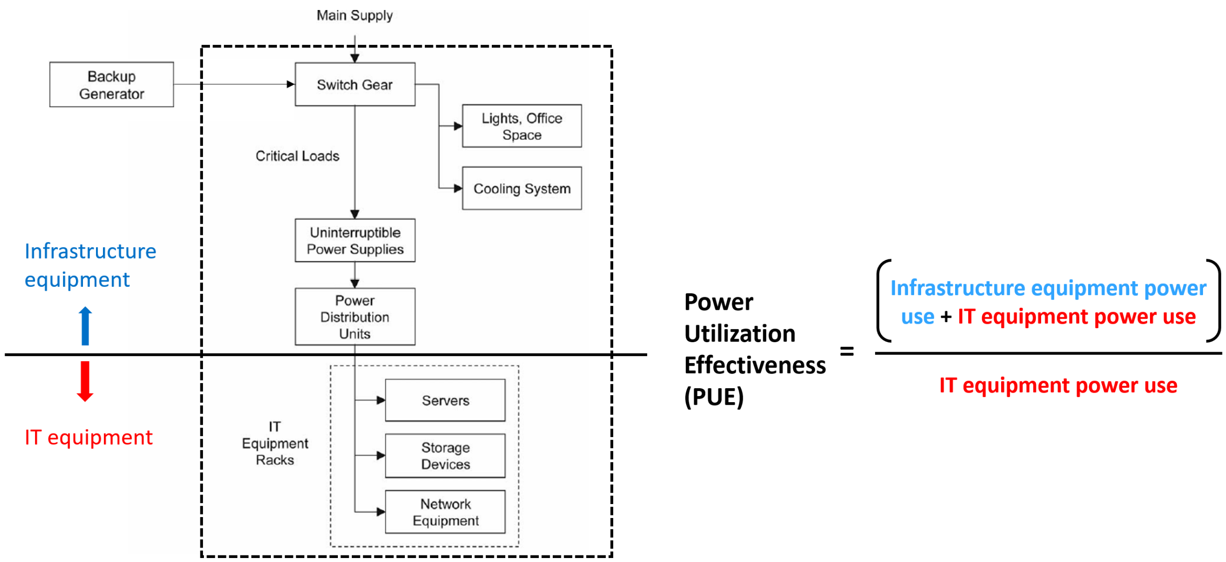


Figure 3: Typical data center electrical components (Brown et al. 2007)

As depicted in Figure 1, the electricity use of infrastructure equipment is quantified in bottom-up models using assumed values of PUE (Koomey 2008,2011; Brown et al. 2007; Masanet et al. 2013; Shehabi et al. 2016; Montevecchi et al. 2020). As shown in Figure 3, PUE is a dimensionless metric that is defined as the ratio of total data center power inputs to IT equipment power inputs (Avelar et al. 2012). In most bottom-up models to date, analysts have assigned PUE values to different data center types to reflect variations in PUE attributable to different cooling technologies, climate zones, and operational efficiency practices. These assumptions are often based on a limited (but growing) body of PUE values reported by data center operators and compiled in surveys by data center industry analysts (Uptime Institute 2021).

The PUE datasets included in our Excel file offer a more flexible approach. Namely, we compiled ranges of PUE estimates generated by a validated physics-based PUE model (Lei and Masanet 2021, 2022) that enable analysts to select PUE values on the basis of the following three elements:

- Data center cooling system type (water-cooled chillers, air-cooled chillers, direct expansion systems, adiabatic cooling[1], use of waterside or airside economizers)
- Climate zone (based on ASHRAE Standard 90.1-2010, Table 2[2])
- Operational efficiency level (point within the range from best to poor efficiency practices)

[1] Simulations are being conducted for adiabatic cooling and results can be added to future dataset updates
[2] Two new climate zones (0A, 0B) have been added to the latest ASHRAE standards, simulations for these climate zones are being conducted and results can be added to future dataset updates

Table 2: PUE data climate zone classification based on ASHRAE Standard 90.1-2010 (Hong et al. 2013)

Climate zone	Climate type	Criteria
1A	Very Hot–Humid	5000 < CDD10 °C
1B	Very Hot–Dry	5000 < CDD10 °C
2A	Hot–Humid	3500 < CDD10 °C ⩽ 5000
2B	Hot–Dry	3500 < CDD10 °C ⩽ 5000
3A	Warm–Humid	2500 < CDD10 °C ⩽ 3500
3B	Warm–Dry	2500 < CDD10 °C ⩽ 3500
3C	Warm–Marine	CDD10 °C ⩽ 2500 and HDD18 °C ⩽ 2000
4A	Mixed–Humid	CDD10 °C ⩽ 2500 and 2000 < HDD18 °C ⩽ 3000
4B	Mixed–Dry	CDD10 °C ⩽ 2500 and 2000 < HDD18 °C ⩽ 3000
4C	Mixed–Marine	2000 < HDD18 °C ⩽ 3000
5A	Cool–Humid	3000 < HDD18 °C ⩽ 4000
5B	Cool–Dry	3000 < HDD18 °C ⩽ 4000
5C	Cool–Marine	3000 < HDD18 °C ⩽ 4000
6A	Cold–Humid	4000 < HDD18 °C ⩽ 5000
6B	Cold–Dry	4000 < HDD18 °C ⩽ 5000
7	Very Cold	5000 < HDD18 °C ⩽ 7000
8	Subarctic	7000 < HDD18 °C

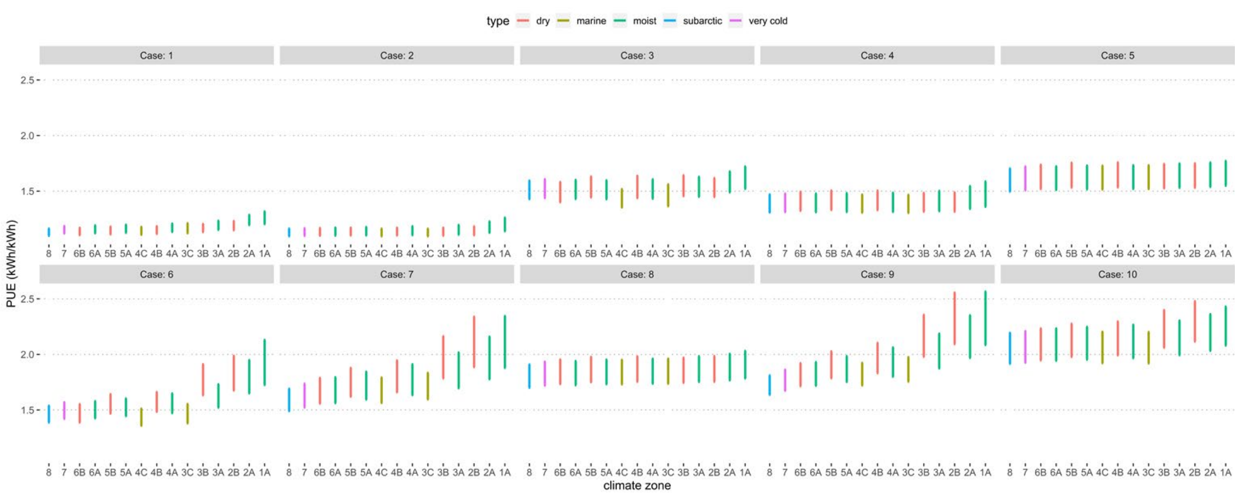


Figure 4: Annual average simulated PUE ranges (best to poor efficiency) by data center type and ASHRAE/IECC climate zone from Lei and Masanet (2022). Note: data center case descriptions are provided in Lei and Masanet (2022).

As shown on the PUE Data tab of the Excel spreadsheet, users can choose assign weighted average PUE values for a given data center market segment and region on the basis of assumed mixes of cooling technologies, climate zones, and efficiency practices. These three elements have been shown in Lei and

Masanet (2021, 2022) to be the major factors governing differences in PUE values across data centers (Figure 4). Users can also explore how shifts in data center locations, cooling system types, and efficiency practices may affect PUE values in the future by changing how these three elements are specified.

Network devices

Network devices within data centers facilitate communication of data between servers, storage devices, other data centers, and the outside internet leading to connected end user devices. In the bottom-up modeling literature, it is increasingly common for network devices to be represented by total counts of network ports residing in data centers, disaggregated by port speed, as opposed to counts of network devices themselves (i.e., the numbers of physical switches, routers, and storage network devices).

The energy use associated with network devices is then derived by multiplying port counts by assumed port wattages and assumed operating hours. Across the literature of bottom-up studies, network device energy use is consistently estimated to comprise a small share of data center energy use compared to servers, storage devices, and infrastructure equipment (Shehabi et al. 2016; Montevecchi et al. 2020; Kemna et al. 2020; Masanet et al. 2020).

To date, estimates of installed stocks of network ports have mostly been derived from commercial datasets on network device shipments compiled by market analysis firms, notably the International Data Corporation (IDC) (Shehabi et al. 2016; Kemna et al. 2020). Only the resulting installed stock estimates have been made available in the relevant studies, not the underlying proprietary device shipment data. Therefore, in this project, we rely on ranges derived from public estimates of installed port counts in the bottom-up literature, disaggregated by port speed (1 Gb, 10Gb, 40 Gb, and 100 Gb). Namely, we rely on data from Shehabi et al. (2016), Montevecchi et al. (2020), and Masanet et al. (2020) normalized to the number of ports per installed server in each study. Network port power data from Kemna (2020) could not be extracted from the available information in the study. Furthermore, we rely on the corresponding port power estimates (W/port) available in each study to derive total network energy use estimates.

The compiled network port installed stock and power use data are contained on the Network Data tab of the Excel spreadsheet.

Storage Devices

Within the bottom-up literature, we identified three major approaches that have been used to estimate the energy use associated with data center storage devices. The differences between approaches are fundamentally related to the structure of the underlying (often proprietary) market data used to estimate the installed numbers or installed capacities of data center storage devices.

In the first approach, analysts consider the equipment stocks and average power utilization of entire rack data storage products, each of which contains multiple storage drives—either hard disk drives (HDDs) or solid state drives (SSDs)—and integrated storage controllers. Key studies taking this approach include the Lot 9 Ecodesign Preparatory Study (Bio by Deloitte 2015), European Commission (2019), and Kemna et al. (2020). These studies utilize the Storage Networking Industry Association (SNIA) taxonomy of Online 1 – 6 products to classify the installed stocks of storage products (SNIA 2022), and estimate the installed stocks of each product class based on proprietary market shipment data, or extrapolations thereof.

In the second approach, analysts consider the equipment stocks of individual storage drives (HDDs and SSDs) and storage controllers alongside per-drive and per-controller power use data to arrive storage energy use totals. Key studies taking this approach include Brown et al. (2007), Masanet et al. (2011), Shehabi et al. (2016), Montevecchi et al. (2020), and Masanet et al. (2020). These studies also rely on proprietary market shipment data, or extrapolations thereof, related to either the total drive capacities (e.g., millions of terabytes (TB)) or total numbers of drives shipped. Notably, several studies indicate growing shares of SSDs over time within national and global installed storage device counts (Shehabi et al. 2016; Montevecchi et al. 2020; Masanet et al. 2020).

In the third approach, installed storage capacities are estimated (e.g., in millions of TB) and disaggregated into the fractions of capacities provided by HDDs and SSDs. Assumptions are made about the average power draw per TB of installed drives of both types to arrive at storage energy use totals. Schneider Electric (2021) was the only reviewed bottom-up study that employed this more high-level modeling approach.

A consistent finding among bottom-up studies to date is that, despite differences in modeling approaches, storage represents the second largest consumer of energy within data center IT equipment behind servers.   However, most studies also find that storage energy use is substantially smaller than server energy use.

Given that estimates of installed storage capacity are more commonly available in the public domain than drive or storage product shipments (see for example Reinsel et al. 2018), and can be translated into numbers of drives based on capacity assumptions (as in Shehabi et al. 2016) in the future, our proposed modeling framework employs the second approach summarized above. Installed storage drives and per-drive and per-controller power usage estimates are derived from data in Shehabi et al. (2016), Montevecchi et al. (2020), and Masanet et al. (2020).

The compiled storage drive installed stock and power use data are contained on the Storage Data tab of the Excel spreadsheet. Global installed storage drive values are assigned to regions in the model on the basis of regional server stocks, per the assumptions in Shehabi et al. (2016) and Masanet et al. (2020).

Servers

Servers are the workhorses of the data center. All previous bottom-up studies have estimated that servers account for the largest share of energy use among data center IT equipment, almost always by a significant margin. For data centers with low PUE values, which are mostly large hyperscale and cloud provider data centers, servers can account for the greatest share of energy use within the entire data center itself (Masanet et al. 2020). Therefore, assumptions related to the quantities of servers in the installed stock and their average operating power greatly influence the overall data center energy use estimates produced by bottom-up studies.

Previous server stock estimates in the bottom-up literature are nearly always derived from proprietary server shipment data compiled by market analysis firms such as IDC and Gartner. These firms track global server markets closely, and work directly with many hardware manufacturers, so their data are considered reliable. They also typically include important details, such as the form factors and brands of servers shipped. However, due to their proprietary nature, the underlying shipment data that analysts use to estimate installed server stocks in different world regions are rarely publicly available.

Depending on the types of proprietary server shipment data used, in the past analysts have categorized server stocks on the basis of their price band (i.e., volume servers, midrange servers, and high-end server) as in Koomey (2008, 2011), Shehabi et al. (2016), Montevecchi et al. (2020), and Masanet et al. (2011, 2020) or on the basis of their form factor (i.e., blade servers, rack servers, and tower servers) as in Bio by Deloitte (2015), European Commission (2019), and Kemna et al. (2020).

Given our aim to utilize only publicly-available, we base our server stock taxonomy on price band given its prevalence in past studies and its use in recent studies that also provide compatible server power use data (i.e., Shehabi et al. 2016, Masanet et al. 2020, and Montevecchi et al. 2020). Furthermore, we conducted a review of publicly-available server shipment values from the two leading server market analysis firms, IDC and Gartner, who often reveal high-level quarterly market analysis values in press releases (IDC 2022; Gartner 2022). The compiled publicly-available server shipment data are summarized in Table 2. Only worldwide shipment totals are released consistently; no consistent regional or country-level shipment data could be found in the public domain.

We note that IDC and Gartner arrive at different annual server shipment values due to their different market research methods, and include both sets of data in our Excel model for use by analysts. We further note that we focused on the period 2010-2018, given that the most recent bottom-up studies that also provide public server power use values for our modeling framework were limited to this time period. However, our framework can be easily updated in the future as more recent data become available.

Table 2: Market analyst firm worldwide annual server shipment data (millions of units)

Year	Firm IDC	Gartner	Average
2010	7.6	8.9	8.3
2011	8.2	9.5	8.9
2012	8.7	9.7	9.2
2013	9.0	9.9	9.4
2014	9.2	10.1	9.6
2015	9.7	11.1	10.4
2016	9.5	11.1	10.3
2017	10.2	11.4	10.8
2018	11.8	12.9	12.4

In our modeling framework, total annual shipment data are disaggregated into volume, midrange, and high-end server categories based on market shares indicated by previous bottom-up studies (Montevecchi et al. 2020; Masanet et al. 2020; Shehabi et al. 2016).

Besides annual server shipments, the other key variable influencing the size of the installed server stock is the average server lifespan assumed. Estimates for the typical lifespan of servers vary across the body of bottom-up literature, with a range of values from around 3 years to around 7 years (Bio by Deloitte 2015; European Commission 2019). In our framework, we allow the user to specify the average lifespan for generating corresponding installed server stock quantities in each server price band.

Worldwide server stocks in each price band are then allocated to specific regions on the basis of regional server workloads and average workload densities estimated by Cisco (2018).

The final variables in the bottom-up calculations for servers relate to the average power draw of servers in each price band. For these values, we compiled datasets for servers from 2010-2018 based on data for each price band in Masanet et al. (2020) and Montevecchi et al. (2020). These selections were based on compatibility with our chosen stock accounting approach and because they represent the most recent compatible server power data in the literature.

The shipment data, lifespan-based stock estimates, regional workload data, and server average power data are contained on the Server Data tab of the Excel model.

Market Segmentation and Regionalization

There is considerable variation in the bottom-up literature on the market segments represented by data center energy use models. For example, Shehabi et al. (2016) segments its model and assumptions roughly on the basis of data center size class, including server closets, server rooms, and localized, mid-tier, high-end, and hyperscale categories. Masanet et al. (2020) segments its model into fewer categories on the basis of market typology and include only traditional, cloud, and hyperscale data centers. Most recently, Montevecchi et al. (2020) categorize three data center types: traditional, cloud, and edge.

We chose to use the simplest typology possible by dividing the model into two market segments: traditional and cloud data centers. This typology has been used by Cisco in its series of Global Cloud Index (GCI) reports (e.g., Cisco 2018). Besides keeping our initial model straightforward for ease of use by EDITS, using this simple typology further enables our framework to estimate installed IT hardware stocks by major world region based on Cisco GCI regional workload data.

Based on Cisco GCI workload data, our model contains datasets and analysis capabilities for the following six world regions: Asia Pacific, Central and Eastern Europe, Latin America, Middle East and Africa, North America, and Western Europe (Cisco 2018).

Projecting Future Energy Demand

Within the data center energy modeling literature, we observed two major approaches to projecting data center energy demand trends.

The first approach relates to the use of an activity indicator to express societal demand for data center services, primarily in top-down and extrapolation-based models (see Table 1). Most commonly, the chosen activity indicator has been global internet traffic, which in the past has been regularly forecasted by Cisco (see e.g., Cisco 2018). Examples of key studies that use internet traffic forecasts to project data center demand growth include Andrae and Edler (2015) and The Shift Project (2019). However, retrospective bottom-up studies have suggested that previous demand projections based on internet traffic tend to overestimate energy growth because efficiency gains through improved hardware and market shifts toward the cloud led to a decoupling of data center energy use and growth in internet traffic (Shehabi et al. 2018).

Additionally, limited operator data also suggests a partial decoupling of data center energy use and data traffic due to efficiency effects, at least for some data center market segments such as content delivery networks (CDNs) (Akamai 2021; CloudFlare 2021). For example, Figure 5 indicates substantial improvement in watts per internet request at CloudFlare, a major edge and CDN company (CloudFlare 2021). With more such data from more data center operators, it may be possible in the future to develop elasticities between data center energy use and incoming/outgoing data traffic for more confident use of data traffic as an activity indicator. However, due to lack of such data currently, projections made on the basis of future data traffic are likely to be highly uncertain.

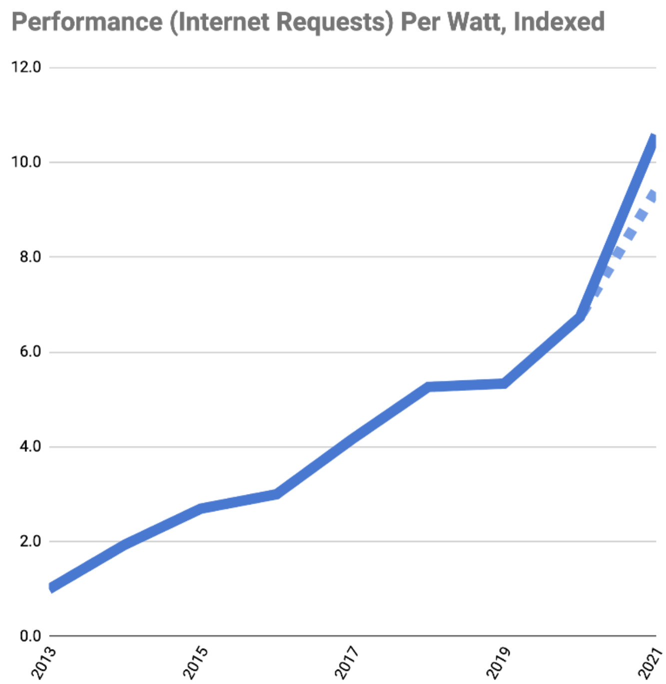


Figure 4: Internet requests per unit server power (W) at CloudFlare, a large CDN provider (CloudFlare 2021)

The second approach relates to the use of technology-level trends analyses and equipment deployment forecasts in bottom-up studies. The latter are typically sourced or derived from proprietary market analysis firms, which often make near-term projections about key technology markets. The former are often based on expert elicitation, trends extrapolation, and analysis of technology characteristics and performance improvement limits. Key examples of bottom-up studies that take this approach are Shehabi et al. (2016), Brown et al. (2007), Kemna et al. (2020) and Montevecchi et al. (2020).

The advantages of this approach are that equipment forecasts are often made by experts with deep understanding of technology markets and technology-level trends can provide much more nuance to overall energy use projections. However, the disadvantages to this approach are that proprietary firm data must often be used, which impedes study transparency, and the need to assess trends for the many technologies that make up the data center technology system can be time- and resource-intensive. In the short run, analysts may consider using short-term projections of equipment stocks and energy performance contained in bottom-up studies that have made national- or regional-level projections to date, notably Shehabi et al. (2016), Brown et al. (2007), Kemna et al. (2020) and Montevecchi et al. (2020).

References

Akamai (2021). Akamai 2020 Sustainability Report. https://www.akamai.com/content/dam/site/en/documents/sustainability/2020-akamai-sustainability-report.pdf

Andrae, A. S., & Edler, T. (2015). On global electricity usage of communication technology: trends to 2030. Challenges, 6(1), 117-157.

Aslan, J., Mayers, K., Koomey, J. G., & France, C. (2018). Electricity intensity of internet data transmission: Untangling the estimates. Journal of Industrial Ecology, 22(4), 785-798.

Bio by Deloitte (2015). Ecodesign Preparatory Study on Enterprise Servers and Data Equipment: ENTR Lot 9. Ref. Ares(2015)5993479 - 22/12/2015.

Avelar, V., Azevedo, D., French, A., & Power, E. N. (2012). PUE: a comprehensive examination of the metric. The Green Grid. White paper #49.

Brown, R. E., Brown, R., Masanet, E., Nordman, B., Tschudi, B., Shehabi, A., ... & Loper, J. (2007). Report to Congress on Server and Data Center Energy Efficiency: Public Law 109-431 (No. LBNL-363E-App.). Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).

Centraal Bureau voor de Statistiek (CBS) (2022). Elektriciteit geleverd aan datacenters, 2017-2020. Netherlands. https://www.cbs.nl/nl-nl/maatwerk/2021/50/elektriciteit-geleverd-aan-datacenters-2017-2020

Cisco Global Cloud Index: Forecast and Methodology, 2016-2021: White Paper, 2018, https://www.cisco.com/c/en/us/solutions/collateral/service-provider/global-cloud-index-gci/white-paper-c11-738085.html

CloudFlare (2021). Designing Edge Servers with Arm CPUs to Deliver 57% More Performance Per Watt. https://blog.cloudflare.com/designing-edge-servers-with-arm-cpus/

Dodd, N., Alfieri, F., De Oliveira Gama Caldas, M., Maya-Drysdale, L., Viegand, J., Flucker, S., Tozer, R., Whitehead, B., Wu, A. and Brocklehurst, F. (2020). Development of the EU Green Public Procurement (GPP) Criteria for Data Centres, Server Rooms and Cloud Services, EUR 30251 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-19447-7, doi:10.2760/964841, JRC118558.

European Commission (2019). COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT: Accompanying the document:Commission Regulation laying down ecodesign requirements for servers and data storage products pursuant to Directive 2009/125/EC of the European Parliament and of the Council and amending Commission Regulation (EU) N°617/2013. Brussels, 15.3.2019 SWD(2019) 106 final

Ganeshalingam, M., Shehabi, A., & Desroches, L. (2017). Shining a Light on Small Data Centers in the U.S. Lawrence Berkeley National Laboratory. Report #: LBNL-2001025. Retrieved from https://escholarship.org/uc/item/8dh8j3kq

Gartner (2022). Newsroom. https://www.gartner.com/en/newsroom

Greenpeace East Asia and the North China Electric Power University (2019). Powering the Cloud: How China's Internet Industry Can Shift to Renewable Energy." http://www.chinawaterrisk.org/research-reports/powering-the-cloud-how-chinas-internet-industry-can-shift-to-renewable-energy/

Hintemann, R., and Clausen, J. (2016). Green Cloud? The current and future development of energy consumption by data centers, networks and end-user devices. In ICT for Sustainability 2016. Atlantis Press.

Hong, T., Chang, W. K., & Lin, H. W. (2013). A fresh look at weather impact on peak electricity demand and energy use of buildings using 30-year actual weather data. Applied energy, 111, 333-350.

Horner, N. C., Shehabi, A., & Azevedo, I. L. (2016). Known unknowns: Indirect energy effects of information and communication technology. Environmental Research Letters, 11(10), 103001.

IEA (2017), Digitalization & Energy, IEA, Paris, https://doi.org/10.1787/9789264286276-en.

International Data Corporation (IDC) (2022). IDC Press Releases. https://www.idc.com/about/press

Kemna, René, Leo Wierda, William Li, Roy van den Boorn, Martijn van ElburgViegand Maagøe, Jan Viegand, Anson Wu (2020). ICT Impact Study: Technical Assistance to the European Commission. ENER/C3/SER/FV 2019-467/01/FWC 2016-542/07/SI2.813170. https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/2020-11/IA_report-ICT_study_final_2020_(CIRCABC).pdf

Koomey, J. G. (2008). Worldwide electricity used in data centers. Environmental research letters, 3(3), 034008.

Koomey, J. (2011). Growth in data center electricity use 2005 to 2010. A report by Analytical Press, completed at the request of The New York Times, 9, 161.

Lei, N., & Masanet, E. (2020). Statistical analysis for predicting location-specific data center PUE and its improvement potential. Energy, 201, 117556.

Lei, N., Masanet, E., & Koomey, J. (2021). Best practices for analyzing the direct energy use of blockchain technology systems: Review and policy recommendations. Energy Policy, 156, 112422.

Lei, N. and E. Masanet (2022). Climate- and Technology-Specific PUE and WUE PredictionsEstimations for U.S. Data Centers Uusing a Hybrid Statistical and PhysicsThermodynamics-Based Approach. Resources, Conservation & Recycling, Under revision.

Masanet, E. R., Brown, R. E., Shehabi, A., Koomey, J. G., & Nordman, B. (2011). Estimating the energy use and efficiency potential of US data centers. Proceedings of the IEEE, 99(8), 1440-1453.

Masanet, E., Shehabi, A., & Koomey, J. (2013). Characteristics of low-carbon data centres. Nature Climate Change, 3(7), 627-630.

Masanet, E., Shehabi, A., Lei, N., Smith, S., & Koomey, J. (2020). Recalibrating global data center energy-use estimates. Science, 367(6481), 984-986.

Montevecchi, F., Stickler, T., Hintemann, R., Hinterholzer, S. (2020). Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market. Final Study Report. Vienna.

National Data Center Application Development Guidelines: 2020. China: POST& TELECOM PRESS, 2020.

Reinsel, David, John Gantz, and John Rydning (2018). Data Age 2025: The Digitization of the World- From Edge to Core. IDC White Paper – #US44413318.

Scheider Electric (2021). Digital Economy and Climate Impact - White Paper. A bottom-up forecast of the IT sector energy consumption and carbon footprint to 2030. Document Number: 998-21202519. https://www.se.com/us/en/download/document/998-21202519/

Shehabi, A., Smith, S. J., Masanet, E., & Koomey, J. (2018). Data center growth in the United States: decoupling the demand for services from electricity use. Environmental Research Letters, 13(12), 124030.

Shift Project (2019). Lean ICT – Towards Digital Sobriety. https://theshiftproject.org/wpcontent/uploads/2019/03/Lean-ICT-Report_The-Shift-Project_2019.pdf

Storage Networking Industry Association (SNIA) (2022). SNIA Emerald Taxonomy. https://www.snia.org/emerald/taxonomyoverview

TechUK (2017). Climate Change Agreement (CCA) for Data Centres, Target Period Two: Report on Findings. https://www.techuk.org/data-centres-programme/data-centres-resource-index.html

TechUK (2020). The UK Data Centre Sector: The most important industry you've never heard of. https://www.techuk.org/data-centres-programme/data-centres-resource-index.html

Uptime Institute (2021). Uptime Institute 11th Annual Global Data Center Survey Shows Sustainability, Outage and Efficiency Challenges Amid Capacity Growth. https://uptimeinstitute.com/about-ui/press-releases/uptime-institute-11th-annual-global-data-center-survey

United States Energy Information Administration (EIA) (2021). 2018 Commercial Building Energy Consumption Survey Data Center Pilot Results. Department of Energy, Washington, DC. https://www.eia.gov/consumption/commercial/data/2018/pdf/2018_CBECS_Data_Center_Pilot_Results.pdf

United States Energy Information Administration (EIA) (2022). Commercial Building Energy Consumption Survey. Department of Energy, Washington, DC. https://www.eia.gov/consumption/commercial/

Wilson, C., Kerr, L., Sprei, F., Vrain, E., & Wilson, M. (2020). Potential climate benefits of digital consumer innovations. Annual Review of Environment and Resources, 45, 113-144.

Energy Technologies Area
Lawrence Berkeley National Laboratory

Assessment of the Roles for and Potential Impacts of Technological and Social Innovations on Energy and CO_2 Emissions

Nina Khanna, Hongyou Lu, Jingjing Zhang, Michelle Johnson-Wang, and Nan Zhou

January 2022

Acknowledgments

The work described in this study was conducted at Lawrence Berkeley National Laboratory and supported by Japan's Research Institute of Innovative Technology for the Earth (RITE) under Contract No. FP00012968 and the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Table of Contents

Acknowledgements i

Table of Contents ii

Table of Figures iii

List of Tables iv

1. Introduction 5

2. Quantitative evaluation of impact of technological and social innovations on energy and CO2 emission reductions 6

   2.1 Building sector 6

      2.1.1 Plug and process load reduction 7

      2.1.2 Cost-savings of Building Technical Innovations 8

   2.2 Industry sector 11

      2.2.1 Demand-Side Innovations in the Cement and Steel Industries 11

      2.2.2 Demand-Side Innovations in Plastic Packaging 12

   2.3 Transport sector 19

      2.3.1 Meta-review of Quantitative Analysis of Impacts of Transport Innovations 19

      2.3.2 Comprehensive Transport Scenario Case Study 26

      2.3.3 Case Studies of New Urban Transport Innovations 27

      2.3.4 Car-sharing replacement of private car ownership 29

   2.4 Cross-sector 29

      2.4.1 Personal carbon trading 30

      2.4.2 Digital Innovations in Influencing Lifestyle Choices 32

3. Assessment of Role for Technological and Social Innovations on Energy Demand Side in Recent Carbon Neutrality Reports 35

   3.1 International Energy Agency (IEA)'s 2021 Net Zero by 2050 Global Roadmap 35

   3.2 United Kingdom Roadmaps 39

   3.3 France's Low Carbon Strategy 42

   3.4 Germany's Climate Action Plan 2050 43

   3.5 Policy Implications and Case Study of Policies for Supporting Innovation in EU Energy and Climate Plans 43

4. References 48

Table of Figures

Figure 1. Incremental Cost of Zero-Energy and Zero-Energy Ready Homes in 4 U.S. Cities........................ 9
Figure 2. Traditional Construction and Prefabrication Cost Comparison 10
Figure 3. Framework on improving material efficiency and reducing energy demand............................. 14
Figure 4. Removing plastic film wrapping for multi-pack tins. 15
Figure 5. Dissolvable cleaning tablets for reusable bottles 16
Figure 6. Loop returning services for reusable packaging 17
Figure 7. Alternative compostable packing made from seaweed and plants 18
Figure 8. Public acceptance on material/resource-efficiency strategies... 19
Figure 9. Transport Mobility Digital Consumer Innovations Reviewed in Wilson et al. 2020 23
Figure 10. Annual Mitigation Potential of Transport Consumption Options in Ivanova et al. 2020 24
Figure 11. Household Preferences for Mitigation Options and CO2 Reduction Potential from Dubois et al. 2019 25
Figure 12. Modeling Parameters for Direct and Indirect Estimations for a Transportation Sector in Dillman et al. 2021.. 26
Figure 13. 2-axis Framework for Scenarios of Behavioral/Urban Form and Technological Changes to Transport in Dillman et al. 2021 27
Figure 14. Impacts of Personal Carbon Allowances.. 32
Figure 15. AntForest Images 33
Figure 16. Example of Google Map Feature on Highlighting Fuel-efficient Routes................................. 34
Figure 17. UK FIRES Absolute Zero Roadmap Milestones by Sector... 40
Figure 18. Disruption and Emissions Abatement Potential for Mitigation Options in U.K. Deep Decarbonization Studies.. 41
Figure 19. Number of Sufficiency Measures by Sector and Type from Zell Ziegler et al. 2021 Review of European National Policy Documents.. 44
Figure 20. Geographical Distribution of Sufficiency Measures from Zell Ziegler et al. 2021 Review of European National Policy Documents.. 45

List of Tables

Table 1. Scope of demand-side innovations in buildings (Year 2) 6
Table 2. Plug and Process Load Technical Control Strategies 7
Table 3. Technological and Social Innovations in Cement and Steel Industries 12
Table 4. Scope of Transport Technological and Social Innovations in Year 1 and 2 Work 20
Table 5. Vehicle and Rebalancing Energy Intensities of Common Forms of Micromobility 28
Table 6. IEA 2021 Net Zero by 2050 Global Roadmap Milestones for Behavior Change in the NZE Scenario 36
Table 7. IEA 2021 Net Zero by 2050 Global Roadmap's Key Behavioral Changes in the NZE Scenario and Policy Implications 38

1. Introduction

In support of the Paris Agreement, many countries have pledged to significantly reduce their greenhouse gas emissions (GHGs) through 2030 or later as part of their Nationally Determined Contributions (NDCs) or revised NDCs. In addition, over 130 countries have also committed to achieving net zero emissions or carbon neutrality by mid-century.[1] The timing and realization of these climate goals are crucial, as the latest Intergovernmental Panel on Climate Change (IPCC) analysis found that immediate, rapid, and large-scale reductions in GHG emissions are needed in the next two decades if limiting global temperature rise to 1.5°C or even 2°C is to remain within reach.[2] To achieve this ambitious climate target, drastic emissions reductions will require not only the development and deployment of more efficient and cleaner technologies and processes but also additional transformative societal changes to complement technological advances. The IPCC's *Global Warming of 1.5°C* Special Report identified key characteristics of 1.5°C-compatible pathways of limiting temperature increase to 1.5°C above the pre-industrial levels that included: rapid and profound near-term decarbonization of energy supply, greater mitigation efforts to reduce demand, increased electrification, adoption of mitigation options aligned with sustainable development goals, and deploying carbon dioxide removal (CDR) at scale before 2050.[3]

Rapid technological advancements and the transformative societal changes enabled by new technologies have the potential to drastically change how people use energy to meet their daily needs, as exemplified by significant shifts toward telecommuting and e-commerce during the Covid-19 global pandemic shutdowns. In order to understand how these new technological and social innovations can reduce energy demand and related emissions, the Research Institute of Innovative Technology for the Earth (RITE) with support by IIASA is leading the Energy Demand changes Induced by Technological and Social innovations (EDITS) Project. In Year 1 of the EDITs project, Berkeley Lab provided research and technical support by conducting comprehensive assessment of global development and trends in technological and social innovations that have implications for energy demand and emissions, and selected global scenarios of lower energy demand due to technological and social innovations from major global modeling institutions to understand how their impacts are considered. Building on this prior work, the research covered in this report aims to include comprehensive analysis and quantitative evaluation of the impact of technological innovation on energy demand-side and subsequent social changes, from a global perspective with emphasis on national examples. In addition, by understanding and comparing different global models and scenarios, the impacts of technological and social innovations on energy demand and CO_2 emission reductions can be quantified and used to inform new and ongoing global and national energy modeling efforts.

This report begins with review and assessment of data and information on quantitative impacts of technological and social innovations on end-use sector specific energy consumption and CO_2 emission reductions in the buildings, industry, transport and cross-sectors. This section focuses on new innovations not included in previous year's work and/or expanded analysis of quantitative evaluations of innovations discussed previously by bringing together multiple data sources and case studies. Next, the report presents a comparative assessment of recently released global and national carbon neutrality roadmaps and reports for selected countries to evaluate if and how lower energy demand due to cross-sector and sector-specific technological and social innovations are expected to contribute to meeting carbon neutrality targets. Lastly, the report will end with some policy implications for demand-side reductions based on national roadmap studies.

2. Quantitative evaluation of impact of technological and social innovations on energy and CO2 emission reductions

This section reviews and assesses quantitative impacts of technological and social innovations on end-use sector specific energy consumption and CO_2 emission reductions, as well as cross-sectoral energy consumption and CO_2 emission reductions. The innovations reviewed here vary by sector but include a combination of new sector-specific innovations that were not included in the previous year's work, new information such as cost-effectiveness of previously reviewed innovations, and expanded analysis of quantitative evaluations of innovations discussed previously by bringing together multiple data sources and case studies. Unlike the previous work, this section also focuses on a more narrowly defined definition of "innovations" following some key characteristics identified in Wilson et al. 2020, including:

- Novel goods and services available with relatively low (<~15%) market shares and/or
- Less than ~10 years since market introduction, corresponding to Rogers' definition for early adopters, *and/or*
- Offers an alternative to mainstream consumption practices *AND*
- Presents clear instances of *potential* energy and emission reduction benefits

2.1 Building sector

In Year 1 report, we provided the key technological and social innovations based on the building life cycle, ranging from design to construction to operation. According to the definition for "innovation" adopted in this year's report, we narrowed down our previous selection of innovations to the following list, see Table 1. We added a new section on "plug load", and updated cost data for the selected technological innovations when available. We removed "building fenestration systems" and "personal space conditioning" as they do not qualify for the definitions aforementioned due to high market penetration rate. Finally, we did not update the cost data for social innovations, mainly because the context in which they are adopted is highly uncertain and are difficult to generalize.

Table 1. Scope of demand-side innovations in buildings (Year 2)

	Design	**Construction**	**Operation**	**Material and equipment**
Technological innovations	Passive house and net zero energy buildings (added cost)	Prefabrication (added cost)	Smart building control technologies; Artificial Intelligence; (added cost)	*Building fenestration systems (removed); Personal space conditioning (removed);* Plug and process load (new)

Social innovations	Innovative ways to downsize: tiny-house movement and co-housing		*Innovative financing models (removed);* Innovative behavioral programs: information based and social interaction (cost data not available)

2.1.1 Plug and process load reduction

Plug and process loads (PPLs) are building electrical loads that are not related to lighting, heating, ventilation, cooling, and water heating, and typically do not provide comfort to the occupants (Sheppy et al. 2013). According to the latest estimates, PPLs consume about 47% of primary energy in U.S. commercial buildings (U.S. DOE, 2022). As buildings become more efficient, the portion of PPLs energy consumption will continue to grow. PPLs are usually difficult to manage because it includes hundreds of device types, from small appliances to computers and lighting, and this remains as one of the major barriers for implementing PPLs reduction strategies.

Fortunately, solutions to reduce PPLs (by up to 50%) are usually simple and could be no cost or low cost, The PPLs control strategies include wireless meter and control systems, advanced power strips, automatic receptacle controls, and integrated controls (see Table 3 for more details).

Table 2. Plug and Process Load Technical Control Strategies

Control Strategies	*Wireless Meter and Control Systems*	*Advanced Power Strips*	*Automatic Receptacle Controls*	*Integrated Controls*
Description	System of smart outlets that measure energy usage and turn devices on/off	Power strips that can be controlled to shut off power to specific appliances	Outlets that are installed in the building and can be controlled to turn devices on/off	Connects lighting, HVAC, and PPL systems to monitor and control them together
PPL Reduction Goal	Control PPLs using a device schedule and understand the PPL energy usage of the entire building	Control the energy usage of specific devices	Control PPLs using a device schedule or occupancy sensors and meet code requirements	Control PPLs alongside lighting controls and understand the PPL energy usage of the entire building.
Characteristics	• Wireless control • Automated system • Full picture of energy use • Device health monitoring	• Shared control of multiple devices • Focus on specific devices	• Wireless control • Automated system • Required for ASHRAE standard 90.1-2019 (ASHRAE 2019) compliance	• Wireless control • Automated system • Full picture of energy use • Device health monitoring • Connecting multiple systems • Interoperability
Metering	Use smart outlets	Use separate plug-in metering devices	Use separate plug-in metering devices	Use building management system

Source: NREL, 2020.

There could also be savings from behavioral strategies, such as manual control, increased education and awareness of using plug load meters and controls such as trainings, emails, signage, videos, and periodic reminders or updates. For large retail buildings, PPL reductions can result in substantial cost savings as well. Combined, technical and behavioral strategies can result in significant energy and cost savings. A NREL study showed an example of annual $40,000 potential energy cost savings associated with a 30% PPL reduction for a large retail building (NREL, 2020).

Plug loads are inefficient partly because they usually require the conversion of grid power from alternating current (AC) to direct current (DC). Existing research has shown that DC power distribution in buildings can yield 4-15% energy savings compared with the same load and energy technologies using AC power (Gerber et al., 2018).

2.1.2 Cost-savings of Building Technical Innovations

Although many technological innovations for reducing energy demand in the buildings sector have relatively low market penetration rates, many of these innovations actually have relatively low incremental costs or are approaching cost-effectiveness.

2.1.2.1 Passive house

In the U.S., a passive house typically costs about 5-10% more than a conventional home. Larger projects can also benefit from the economy of scale as the cost differential decreases with larger floorspace. For example, a multifamily passive building typically only costs 0-3% more than a building built to an EnergyStar baseline (Passive House Alliance, 2022).

2.1.2.2 Net Zero Buildings

Zero-energy and zero-energy ready homes currently make up less than 1% of the U.S. residential market, but their incremental costs compared to conventional homes that meet the building code baseline are decreasing. Due to performance improvements in building shells and highly efficient heat-pump heating, ventilation and air conditioning (HVAC) systems, LED lighting, high efficiency appliances, surveys of zero-energy ready homes in 4 major U.S. cities found an average cost premium of only 1.8% (Petersen et al. 2019). Adding solar PV generation system to produce electricity to meet the zero-energy ready home's total demand, in essence making it a zero-energy home, the average cost premium increases but is still only 7.3% compared to code-compliant homes (Petersen et al. 2019). Figure X shows the premium cost differentials across the 4 U.S. cities.

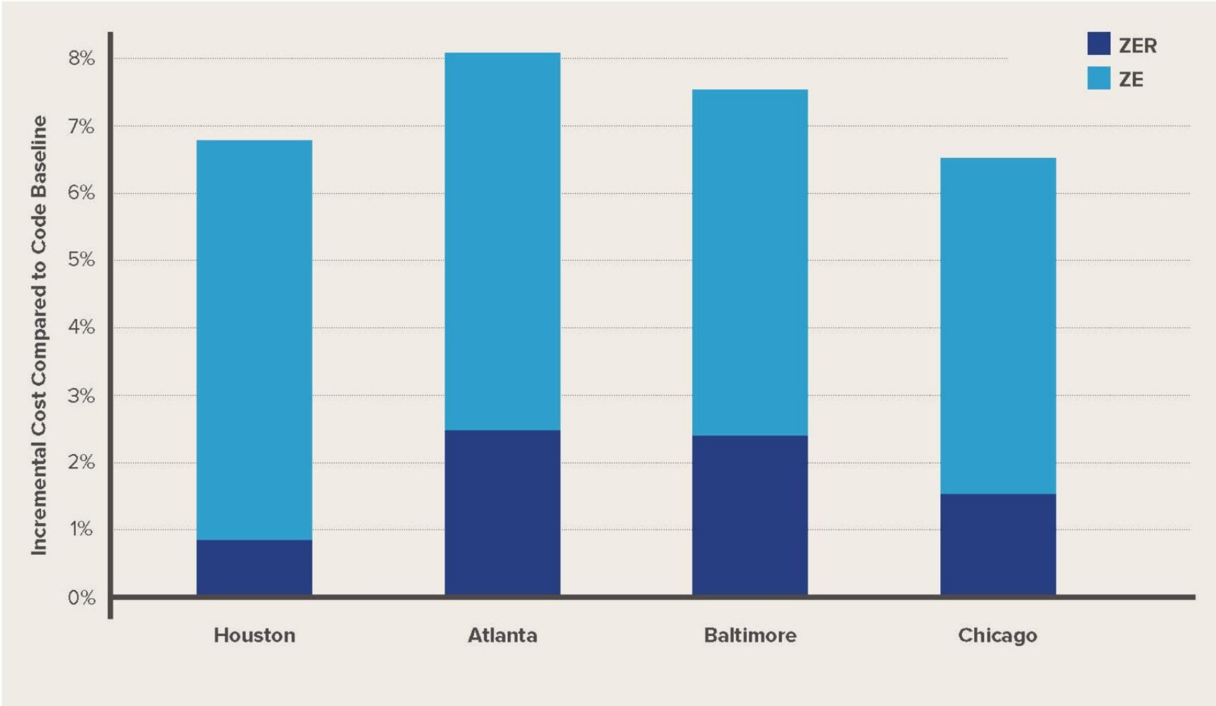


Figure 1. Incremental Cost of Zero-Energy and Zero-Energy Ready Homes in 4 U.S. Cities
Source: Petersen et al. 2019

2.1.2.3 Prefabrication

Prefabrication through the production of standardized structural components is gaining new attention with the maturing of digital tools and potential in reducing project construction timelines significantly. Although prefabrication costs are still relatively high today, a recent McKinsey analysis identified growing potential to yield significant cost savings on the order of 20% total savings as shown in Figure 2 below. However, the net cost savings will depend highly on a combination of labor savings, but potential increased logistics or materials costs, and could run the risk of up to 10% net cost increases.

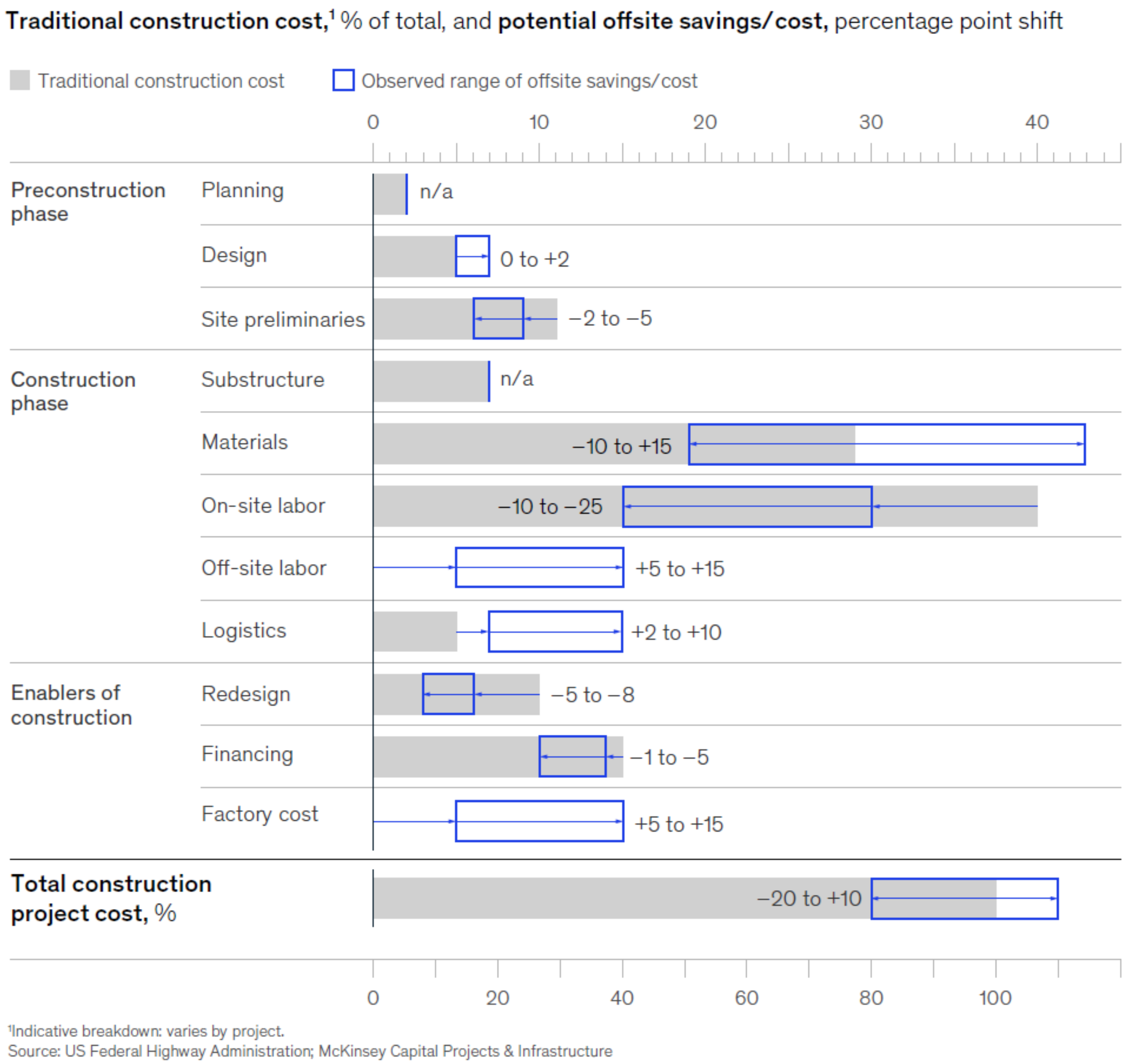


Figure 2. Traditional Construction and Prefabrication Cost Comparison
Source: Betram et al., 2019.

2.1.2.4 Smart building control technologies (IoT)

Building management systems (BMS) support smart buildings by allowing building owners and tenants to monitor, control, maintain and manage building technology systems through sensors, software, a network and cloud-based data storage. However, because it requires specialized installation, programming and maintenance and are often tailor designed for large-sized buildings, BMS can be very expensive. Their average costs can range from US$2.50/square foot to US$7.00/square foot, totaling up to US$250,000 to US$700,000 additional cost for a 100,000-square foot building (Tracy, 2016). The longer than four-year payback period for all but the largest buildings makes BMS a challenge for increased deployment, but new technologies are showing potential for reduced costs. Adding in Internet of Things (IOT)-based controls and monitoring such as through low-powered networks, inexpensive wireless sensors, on-premise gateways and cloud analytics can reduce the deployment costs of BMS by 30% (Tracy, 2016).

In addition to IOT, machine-based artificial intelligence (AI) is also being used to improve BMS with potential cost savings and carbon reductions demonstrated. A "Flex2X" AI-system developed by UK company Grid Edge analyzes data from a building's existing energy management system and from other data sources and uses AI algorithms to optimize the building's energy use in real-time. The effectiveness of such a BMS in optimizing building energy use not only helps improve thermal comfort and energy efficiency, but also has potential to reduce costs and CO_2 emissions through load-shifting and optimization. Grid Edge's system has measured impacts including cost savings and revenue generation equivalent to greater than 10% of annual on-site energy costs, and up to 40% reduction in CO_2 emissions through load-shifting and efficiency measures (IEA, 2019).

2.2 Industry sector

2.2.1 Demand-Side Innovations in the Cement and Steel Industries

In Year 1's project, we looked into technological and social innovations to reduce energy demand, with a focus on cement and steel industries, given the two industries' significant energy and CO_2 impacts globally. We provided descriptions of these innovations, in addition to savings potential, applicability, barriers, technological readiness levels, and case studies (if any). A summary of the demand-side technological and social innovations is shown in Table 3. Details of these measures can be found in the Year 1 Report.

Table 3. Technological and Social Innovations in Cement and Steel Industries

	A. Reduce demand (Production side)	**Saving Potential**	**B. Shift demand** (Shift to new/lower energy demand materials)	**Saving Potential**	**C. Avoid demand** (Demand side)	**Saving Potential**
Technological innovations						
Cross-cutting	1. Additive manufacturing	~500 kg of potential reduction in weight of a single aircraft engine; can be up to 90% in reduction of material needs; 75-98% energy savings; reduces fabrication time and increases flexibility	1. Smart manufacturing	Varies by level and by specific application	1. Extend building lifetime	A 50% increase from the baseline (e.g., increase building lifetime from 30 years to 60 years) would result in 14% decrease in cement demand
	2. Post-tensioning	20% concrete reductions (and 30% steel reduction)			2. Integrative design	Studies have shown that integrative design can achieve energy savings of 30% to 60% with paybacks of a few years when retrofitting existing industrial plants, and can achieve 40-90% energy savings with lower capital costs for new industrial facilitie
	3. By-product synergy	Savings may include energy, material, CO_2, and water savings, and reduced waste disposal; potential varies by project			3. Component reuse	68% of concrete use for new construction projects could be saved
Cement/ Concrete	4. Use of alternative fuels	For non-biomass alternative fuels, the CO_2 savings are about 20-25% reduction in CO_2 emissions; for biomass, it is estimated that this could have a 30% CO_2 emission reduction potential. Studies have estimated the energy savings would be 0.6 GJ/t clinker.	2. Clinker substitution	45% cement reduction in all applications of cement	4. Reduce overdesign	By reducing over-specification in the design process, it is estimated that 20% cement reduction could be achieved in structural elements
			3. Material substitution	Reduces 25-42% of concrete		
			4. Alternative cement chemistries	6-97% reduction in process CO_2 intensity, varies by type of alternative cement	5. Improving concrete quality	15% cement demand reduction
					6. Recycling of concrete	5.2 kg CO_2 per tonne of recycled concrete aggregate
					7. Reduce construction wastes	Reducing 1-3% of cement used in construction
Steel	5. Improving product manufacturing yields	Improving sheet metal material efficiency to 70% (from 56%) can reduce CO_2 emissions by 26% and reduce sheet metal car structural costs by 24%	5. Lightweight materials	30% of the mass of a standard I-beam could be saved	8. Remanufacturing and reuse	More than 50% energy savings
Social innovations						
Cross-cutting	7. Extended producer responsibility				10. Intensified use of existing building stocks	10-14% cement demand reduction if residential and non-residential floor space per capita is reduced by 7% by 2060
	8. Establish product service systems				11. Circular business models	car-sharing has the potential to reduce the demand by 50%; sharing the services instead of goods, such as share and repair, non-market and community services have a median mitigation potential of 0.3 tCO_{2eq} per capita

2.2.2 Demand-Side Innovations in Plastic Packaging

In Year 2 of the project, we took a deep dive into the plastics industry, with the same focus on technological and social innovations to reduce demand. We chose plastics due to its energy-intensive production process, fossil-fuel based feedstock, difficulty to recycle, increased amount of plastic wastes in ecosystems, and its ubiquitous use in people's daily lives.

We added technological and social innovations to avoid, shift, and reduce demand for plastics, especially for plastic packaging. These measures include: improved material efficiency in packaging, development of circular economy business models, use of high-performance polymers to increase product lifetime, mechanically recycle of plastics, material substitution (e.g., use of biocomposites). We also provided a brief look into public acceptance of social innovations to reduce demand, such as extended producer responsibilities and establishment of product service systems.

Sections first provided the background information on why it is important to reduce energy demand in plastics industry. Then, we provide technological and social innovations on the demand side to reduce energy demand associated with plastics.

2.2.2.1 Why Plastics?

Plastics are used in people's daily lives, such as plastic containers, plastic bottles, and shopping bags. Plastic production has increased 26% from 334 million metric tons (Mt) to 422 Mt between 2010 and 2016 (Law et al. 2020). The share of plastics in solid waste increased from 10% to 12% globally, reaching 242 Mt in 2016 (Hoornweg and Bhada-Tata 2012; Kaza and Yao 2018). Studies such as (Jambeck et al. 2015) estimated that on an annual basis about 8 Mt of plastic pollution enters the ocean. On a per-capita level, studies found that the United States produce the highest level of plastic waste, at about 105-130 kg per person per year. UK, South Korea, and Germany also have some of the highest per-capita plastic waste generation, producing 99 kg/person, 88 kg/person, and 81 kg/person annually, respectively. On average, EU-28 produces 55 kg/person per year, while India and China produce about 20 and 16 kg of plastic wastes per person per year (Law et al. 2020).

The production of plastics as well as end-of-life if plastics are burnt are associated with energy and greenhouse gas (GHG) impacts. Industrial Transformation 2050 estimated that about 2.3 tonnes of CO_2 are emitted per each tonne of plastics produced. Another 2.7 tCO_2/t plastics are embedded in the materials (Material Economics 2019). If the plastics are incinerated after disposal, a total of 5 tCO_2/t plastics would be emitted. If the plastics are landfilled, emissions could be delayed. However, landfill faces challenges of land requirements and plastic waste pollution.

In Europe, the largest use of plastics is in packaging, accounting for 40% of all plastics use. Another 30% of the plastics are used in buildings, construction, and automotive sectors, as insulation, pipes, floors, finishing, and other purposes (PlasticsEurope 2018). The other 30% of the plastics are used for a range of products such as electronics, medical equipment, and household products (PlasticsEurope 2018). Plastic materials vary by properties and end-uses too. In packaging, PET is the most common plastic material. PVC is mostly used in construction. The Europe, five plastic material: polyethene (PE), polyprophen (PP), polystyrene (PS)/EPS, polyvinylchloride (PVC), and polyethylene terephthalate (PET) account for 75% of the use (Material Economics 2019).

2.2.2.2 Framework on Demand-Side Solutions

To reduce energy, emissions, and environmental impacts of plastics, this section focuses on demand-side solutions, during the product design, production, use, and circulation stages. Measures such as direct elimination of materials, innovative ways to eliminate the use of plastic packaging, material efficiency in product design, use of higher quality materials, material substitution, extending product lifetime, repair, reuse, and return business models, as well as recycling and composting are discussed here. This framework of reducing energy demand of plastic use from the demand-side is summarized in Figure 3. In addition, a number of supply-side solutions are developed or emerging, such as improving energy efficiency, fuel switching, electrified cracking and polymerization, CCS on refining, cracking and polymerization, and CCS on end-of-life incineration. This section only emphasizes the demand-side solutions.

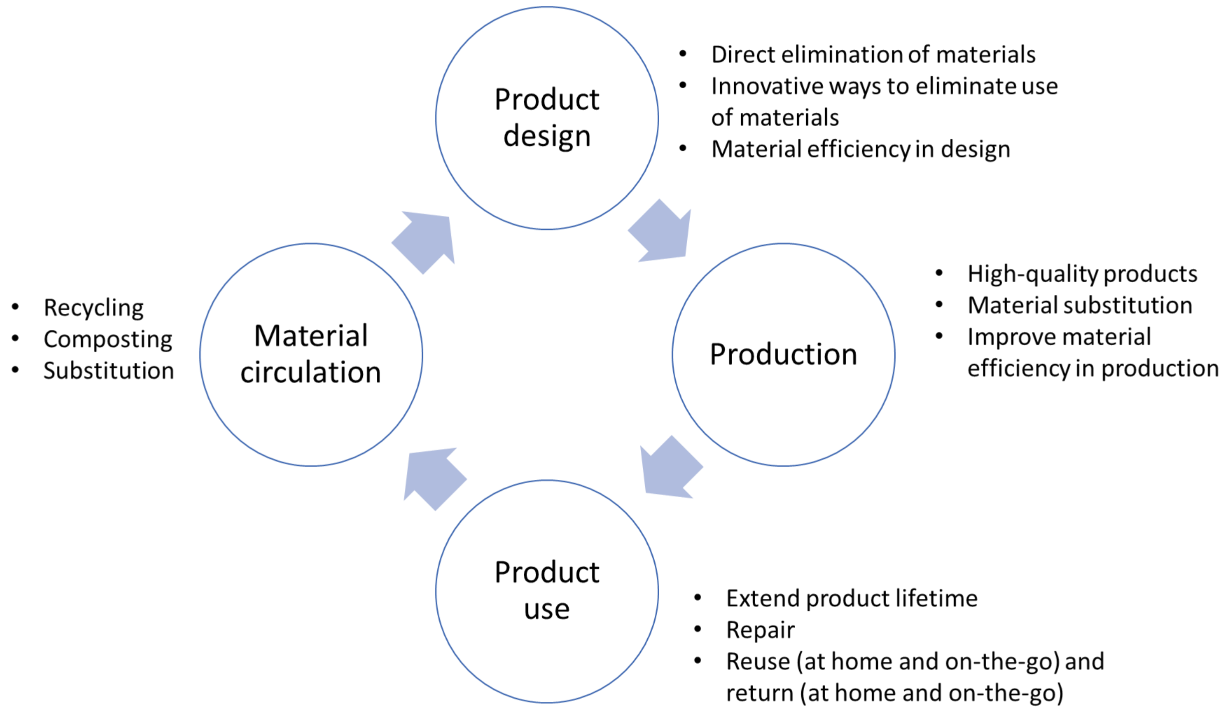


Figure 3. Framework on improving material efficiency and reducing energy demand

2.2.2.3 Materials efficiency in packaging, design, and using high-quality products

Currently, because plastics are light and low-cost, the use of plastics is not optimized. Multiple opportunities exist to improve the ways plastics are used. For example, experts estimated that plastics used for food and consumer goods packaging can be reduced by 20% or more without compromising functionality (Material Economics 2019).

If a packaging does not serve an essential function (such as containment, convenience, communication, efficiency), it can be directly eliminated. For example, secondary plastic wrapping can be removed from multi-buy items, e.g., canned foods, beverages, and snack packages. Unnecessary tear-offs on products such as water bottles and jars, as well as unnecessary plastic film for fresh produce, clothing, cosmetics, and greeting cards can be removed (The Ellen MacArthur Foundation 2020).

In UK, starting in March 2020, the supermarket chain Tesco removed plastic wrapping form its multipack tins, such as soups, beans, and tomatoes (Figure 4). According to Tesco, 40% of the Tesco customers buy tinned multipacks with 183,000 sold across its stores every day. By eliminating plastic film wrapping on its multi-buy tins, Tesco estimated that it could eliminate 67 million pieces of film per year, or 350 tonnes of plastics annually (BBC, 2020). Customers can still buy multi-packs and the deals are automatically applied at the checkout counters for loose tins. Similar actions are also taken by Waitrose & Partners, removing plastic film wraps from multi-buy deals in a trial in 17 of its stores (Waitrose, 2019).

Figure 4. Removing plastic film wrapping for multi-pack tins.
Source: BBC, 2020.

Other similar examples are taken by other retailers and vendors. For example, Walmart Canada eliminated plastic wrap from fresh fruits and vegetables (e.g., bananas and peppers), saving about 93 tonnes of plastic film per year (Walmart, 2019). Nestle removed the bottle cap sleeves from Nestle Pure Life water bottles, and added a label says "If it clicks, it's safe". SonaeMC, the food retailer in Portugal has removed plastic tear-offs from glass jars for olives and jellies (The Ellen MacArthur Foundation 2020).

Innovative solutions are also been implemented to reduce and/or eliminate plastic packaging. For example, edible packaging that can be eaten with the product and dissolvable packaging that can be dissolved in water. Apeel, who manufactures and distributes an edible coating that can be applied to products claims that this would eliminate plastic wrapping on produce (e.g., cucumbers, avocados, limes, lemons, apples), reduce food wastes, and save 18-80% of carbon dioxide emissions based on life-cycle assessment (The Ellen MacArthur Foundation 2020). Dissolavble packaging are used by leading brands of detergent. Some companies are also working expanding the application to food applications, such as instant coffee, pre-measured spices, single-serving condiments.

Materials-efficient design principles can be applied to reduce the total amount of materials used. For example, some companies (e.g., Lush Cosmetics, Lamazuna, Ethique, Amor Luminis, Bars over Bottels) are redesigning liquid products, such as shampoos and other hair, body, and beauty care products, as solid products to eliminate plastic packaging. Some other companies (e.g., Danone) developed "label-free" plastic water bottles, replacing plastic wrapping labels with embossed water bottles. Using high-performance polymers can also increase product lifetime and reduce demand on new products.
Other strategy examples include extended producer responsibility, remanufacturing, and establishment of product service systems. A study found that strategies that encourage efficient products and product lifetimes (through design for product durability, recyclability and or/reusability, as well as strategies that extend and optimize the useful product lifetimes) have the higher potential to reduce emissions, comparing to product sharing strategies (Cherry et al. 2018).

2.2.2.4 Circular business models: right to repair, reuse, remanufacture, and product-sharing

Increasing product lifetime and intensifying produce use can have significant impact on reducing demand of new products. New business models that allow, encourage, and incentivize customers to repair, reuse, remanufacture, and share products can extend the product lifetime and increase the product use intensity, and thus reduce demand on new plastics. For example, car-sharing has the potential to reduce the demand by 50% (Material Economics 2019).

New business models are emerging to allow consumers to reuse their plastic bottles, jars, containers, etc. through refill stations (customers refill at designated places, e.g., stores), refill services (customers refill their containers at home), return stations (users return packaging to a store or a drop-off point), and return services (packaging is picked up by a collection service). For example, some companies (e.g., Everdrop and Blueland) are offering dissolvable cleaning tables that can be dropped into reusable bottles at home, as shown in Figure 5.

Figure 5. Dissolvable cleaning tablets for reusable bottles
Source: Blueland, 2022.

Some companies (e.g., MIWA and Nestle, Unilever and Walmart Mexico) provided pilot refill-on-the-go service. Some food preparing and delivery companies (e.g., VYTAL) are providing reusables to customers and users can drop off empty packing at designated sites or have the packaging picked up at the next delivery. Loop, working with major brands (e.g., Tide, Kroger, and Walgreens) is providing reusable packaging to customers. After use, customers do not need to clean or sort the container. It can be picked up or dropped off at a participating store. The container is then cleaned, refilled, and sold to another customer, shown in Figure 6 (The Ellen MacArthur Foundation 2020). LCA studies show that packaing used by Loop is 22-45% less carbon emissions than single-use packaging (The Ellen MacArthur Foundation 2020).

Figure 6. Loop returning services for reusable packaging
Source: Loop, 2022

A meta-study that reviewed climate change mitigation potential of 771 consumption options found that sharing the services instead of goods, such as share and repair, non-market and community services have a median mitigation potential of 0.3 tCO_{2eq} per capita (Ivanova et al. 2020).

2.2.2.5 Mechanical recycling

Currently, recycling rates are very low globally. Studies estimate at around 14% in the plastic packaging field (Hahladakis and Iacovidou 2018). Mechanical recycling refers to sort, shred, clean, melt and process plastic wastes into new plastic products. Comparing to traditional plastic production processes, which involve fossil fuels and high temperatures, mechanical recycling requires much lower temperature and fossil fuel inputs. While mechanical recycling does not avoid new energy inputs by 100%, it can reduce energy required to produce new plastic products and mitigate CO_2 impacts. CO_2 emissions of mechanically recycle plastics are estimated to be around 0.5tCO_2/t, instead of 2.3 tCO_2/t in primary plastic production. Mechanical recycling also avoids CO_2 emissions associated with end-of-life incineration.

For example, Magnum (ice cream brand) launched its pilot in 2019 to use recycled polypropylene plastic in its ice cream tubs and rolled out 7 million tubs in 2020. The recycled polypropylene plastic is certified from SABIC's TRUCIRCLE initiative (Mohan, 2021). Magnum estimated that about 160,000 kg of certified plastics are used (Cornall, 2020). Magnum's goal is to use recycled plastic materials in all its tubs by 2025.

2.2.2.6 *Material substitution*

Switching to low-carbon materials, such as sustainability sourced fiber alternatives offers potential to reduce demand on new plastics. While multiple factors play a role in material selection, a study found that up to 25% of current plastics used for packaging (in bottles and caps, bags, boxes, cups, tubs, jars, blister packs, pouches, trays, and warsp) can be substituted, in principle, with fiber-based alternatives, without compromising on unique properties of plastics (e.g., formability, transparency, etc.) (Material Economics 2018). The study also found that 5% of plastics used in structural elements can be replaced with biocomposites.

For example, Ooho produces dissolvable packaging for beverages and condiments from seaweed (Figure 7). The company developed compostable "blob" (less than 100 ml) as alternative to traditional small packets in take-outs and beverages.

Figure 7. Alternative compostable packing made from seaweed and plants
Source: Notpla, 2022.

It should be noted while sustainable biomass or biomass materials could be used to substitute some portions of plastics use, it alone cannot meet today's demand for plastics. Material substitution need to be strategically utilized as one of the solutions that fits into the overall system of increased material efficiency, circular business models, high degrees of mechanical recycling, and use of low-carbon materials. In addition, customer behavior and use pattern also play a key role in the life-cycle environmental impacts of different materials. A life-cycle assessment (LCA) based study that compared the energy impact, water consumption, as well as the global warming potential (GWP) between reusable alternatives and single-use plastic products found that nine out of twelve reusable alternatives were able to breakeven in all three indicators. The environmental impact of these reusable alternatives depend on the number of uses, consumer behavior, and carbon intensity of the grid (for GWP) (Fetner and Miller 2021).

Under Material Economics' "Circular Economy" pathway, by relying on demand-side opportunities, including 20% reduction in packing, reuse up to 5% of end-of-life products, and increasing mechanical recycling rate from 10% to 30%, the study estimated that EU's plastic production level could be reduced from 72 Mt (baseline level in 2050) to 52 Mt by 2050, with 62% of plastics reduced through mechanical and chemical recycling and 38% of plastics produced from biomass feedstock. The estimated abatement cost is about -€154 euros/tCO_2 (-$173/t$CO_2$) for mechanical recycling and €32/tCO_2 ($36/t$CO_2$) for materials efficiency and circular economy strategies (Material Economics 2019), significantly lower than other supply-side solutions.

2.2.2.7 Public acceptance

A study that based on UK public stakeholder engagement found that there is strong public support as well as conditions of acceptance on material/resource-efficiency strategies, shown in Figure 8 (Cherry et al. 2018). Overall, efficient products type of strategies received the highest support, showing public desires to reduce waste and protect the environment. Product sharing type of strategies also were also received positively due to increased personal utility, affordability, and convenience, and a number of co-benefits were pointed out, such as increased community cohesion and social interactions. Strategies to increase product lifetimes were received positively in general, especially on extending producer responsibility to increase product lifespans. However, the study found participants have a range of different concerns about paying for services, i.e., Product Service Systems.

	Overall public reception	Conditions of acceptance
Efficient Products	++ Overall + Product light-weighting + Modular and repairable design ++ Reduced/recyclable packaging	Policies/initiatives should focus on maintaining: Affordable range of products and services Product safety and quality guarantees
Product Sharing	+ Overall + Reusing vehicles and products +/− Sharing of vehicles and products + Library of things	Policies/initiatives should focus on maintaining: Trust between peers, organizers and businesses Product safety, quality and hygiene Affordable and convenient access to products
Product Lifetimes	+/− Overall ++ Extended producer responsibility + Remanufacturing − Product service systems	Policies/initiatives should focus on maintaining: Trust between businesses and consumers Fair and upfront distribution of responsibility Long-term affordability (avoiding lock-in)

++, very positive; +, positive; +/−, divergent; −, negative.

Figure 8. Public acceptance on material/resource-efficiency strategies
Source: Cherry et al. 2018.

2.3 Transport sector

2.3.1 Meta-review of Quantitative Analysis of Impacts of Transport Innovations

Previous work in the Year 1 report covered a wide-range of innovations that could reduce passenger and freight transport energy demand and related CO_2 emissions, but the quantitative impacts were based on a limited number of studies and were mostly point or range estimates for a given innovation. More recently, multi-sectoral reviews that quantifies energy or emissions reduction impacts of social and technological innovations within a defined scope based on extensive literature review have been published. This section presents a meta-analysis of three recently published reviews (Wilson et al. 2020, Dubois et al. 2019, and Ivanova et al. 2020) by focusing specifically on the findings for innovations in the transport sector. Table 4 shows the scope included in Year 1 work in black, with the overlaps in the meta-analysis shown in blue, and the new innovation shown in blue italics.

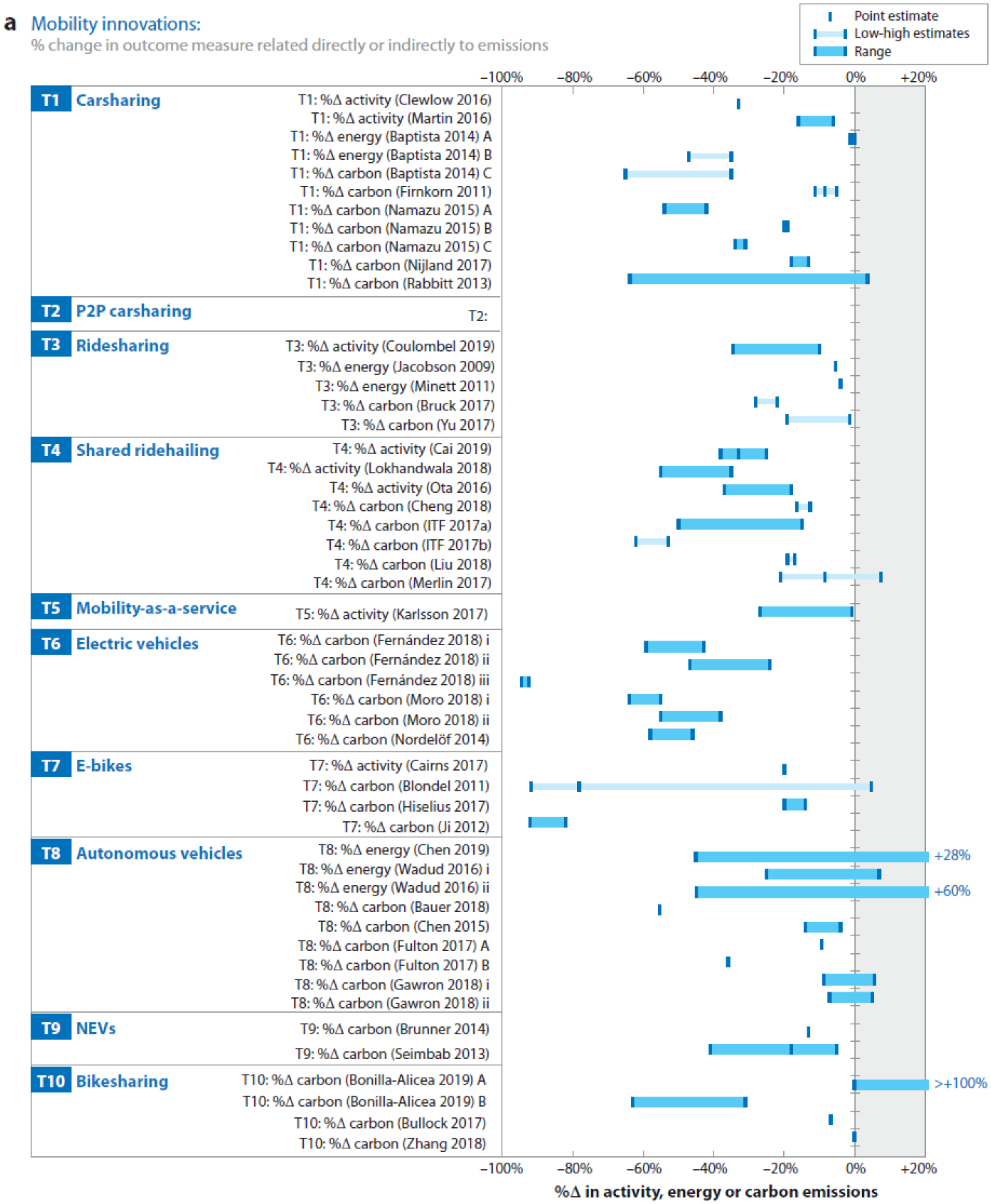
Table 4. Scope of Transport Technological and Social Innovations in Year 1 and 2 Work

	Avoid	**Improve**	**Shift**
Technological	(P) Information Communication Technology and Digitalization	(P) Autonomous cars	(P) Information Communication Technology/Internet of Things/Mobility as a Service
		(F) Automated Vehicles: Platooning (F) Logistical improvements/smart freight	(F) Multi-modal last-mile logistics
Social	(P&F) E-commerce	(P) Motorized vehicle ride-sharing (P) Right-sizing, increasing vehicle occupancy	(P) Bike-sharing (P) Aviation to rail (P) Active mode *(P) Micromobility (NEW)*

Note: blue font denotes innovations included in Year 1 and in Year 2's meta-review. Blue italic font indicates new innovation added in Year 2's work.

In terms of scope, all three studies focused on transport or mobility innovations from the perspective of the consumer. In other words, all three studies focused exclusively on innovations that change passenger mobility activity, modes, or technologies, without including similar applications or additional innovations for the freight transport sector. Wilson et al. 2020 uses specific screening criteria for innovations that includes: novel goods or services with low (<15%) market shares, digital or digitally enabled in nature, offers an alternative to current mainstream practices, and presents clear evidence of potential emission reduction benefits. Ivanova et al. 2020 also used screening criteria for its literature review to focus on life-cycle analysis studies that analyzed consumer-facing interventions with direct or indirect reductions in consumption, direct improvement in purchasing behavior or indirect improvements in consumption through changes in disposal behavior. Dubois et al. 2019 adopted a different methodology to analyze potential reductions in household consumption through household preference surveys and interviews conducted in four cities in France, Germany, Norway and Sweden. In light of these methodological and scoping differences, some overarching similarities in key findings and differences are identified for transport-related innovations.

For Wilson et al. 2020 and Ivanova et al. 2020, both comprehensive literature review covered wide ranging studies with different methodologies, sample sizes, geographies, time horizons, and assumptions, and include point estimates, high and low ranges, and other data syntheses. Based on its screening, Wilson et al. 2020 found that potential reductions in activity, energy consumption or greenhouse gas emissions are consistently identified with many innovations having over 20% reduction in activity, energy and/or carbon emissions. For the transport sector specifically, the review found large variations in magnitude of reduction potential for a given innovation, with telecommuting identified as one of only two innovations with broad convergence of 0 – 10% reduction potential across multiple studies as seen in Figure 9 (Wilson et al. 2020). It found a weaker evidence base for transport demand reductions from the most novel innovations such as those with very low market shares and influenced activity changes such as mobility-as-a-service innovations. Similarly, Wilson et al. 2020 found that measures based on "avoid" strategies such as virtual mobility as a substitute are among the most difficult to quantify because the baseline/reference point is counterfactual. Lastly, it found that increased transport demand resulted from substitution effects or induced demand effects for certain innovations, including up to 20% increase in energy consumption from autonomous vehicles and CO_2 emissions from bike-sharing.


a Mobility innovations:
% change in outcome measure related directly or indirectly to emissions
Point estimate
Low-high estimates
Range
−100% −80% −60% −40% −20% 0% +20%
T1 Carsharing
T1: %Δ activity (Clewlow 2016)
T1: %Δ activity (Martin 2016)
T1: %Δ energy (Baptista 2014) A
T1: %Δ energy (Baptista 2014) B
T1: %Δ carbon (Baptista 2014) C
T1: %Δ carbon (Firnkorn 2011)
T1: %Δ carbon (Namazu 2015) A
T1: %Δ carbon (Namazu 2015) B
T1: %Δ carbon (Namazu 2015) C
T1: %Δ carbon (Nijland 2017)
T1: %Δ carbon (Rabbitt 2013)
T2 P2P carsharing
T2:
T3 Ridesharing
T3: %Δ activity (Coulombel 2019)
T3: %Δ energy (Jacobson 2009)
T3: %Δ energy (Minett 2011)
T3: %Δ carbon (Bruck 2017)
T3: %Δ carbon (Yu 2017)
T4 Shared ridehailing
T4: %Δ activity (Cai 2019)
T4: %Δ activity (Lokhandwala 2018)
T4: %Δ activity (Ota 2016)
T4: %Δ carbon (Cheng 2018)
T4: %Δ carbon (ITF 2017a)
T4: %Δ carbon (ITF 2017b)
T4: %Δ carbon (Liu 2018)
T4: %Δ carbon (Merlin 2017)
T5 Mobility-as-a-service
T5: %Δ activity (Karlsson 2017)
T6 Electric vehicles
T6: %Δ carbon (Fernández 2018) i
T6: %Δ carbon (Fernández 2018) ii
T6: %Δ carbon (Fernández 2018) iii
T6: %Δ carbon (Moro 2018) i
T6: %Δ carbon (Moro 2018) ii
T6: %Δ carbon (Nordelöf 2014)
T7 E-bikes
T7: %Δ activity (Cairns 2017)
T7: %Δ carbon (Blondel 2011)
T7: %Δ carbon (Hiselius 2017)
T7: %Δ carbon (Ji 2012)
T8 Autonomous vehicles
T8: %Δ energy (Chen 2019)
T8: %Δ energy (Wadud 2016) i
T8: %Δ energy (Wadud 2016) ii
T8: %Δ carbon (Bauer 2018)
T8: %Δ carbon (Chen 2015)
T8: %Δ carbon (Fulton 2017) A
T8: %Δ carbon (Fulton 2017) B
T8: %Δ carbon (Gawron 2018) i
T8: %Δ carbon (Gawron 2018) ii
+28%
+60%
T9 NEVs
T9: %Δ carbon (Brunner 2014)
T9: %Δ carbon (Seimbab 2013)
T10 Bikesharing
T10: %Δ carbon (Bonilla-Alicea 2019) A
T10: %Δ carbon (Bonilla-Alicea 2019) B
T10: %Δ carbon (Bullock 2017)
T10: %Δ carbon (Zhang 2018)
>+100%
−100% −80% −60% −40% −20% 0% +20%
%Δ in activity, energy or carbon emissions

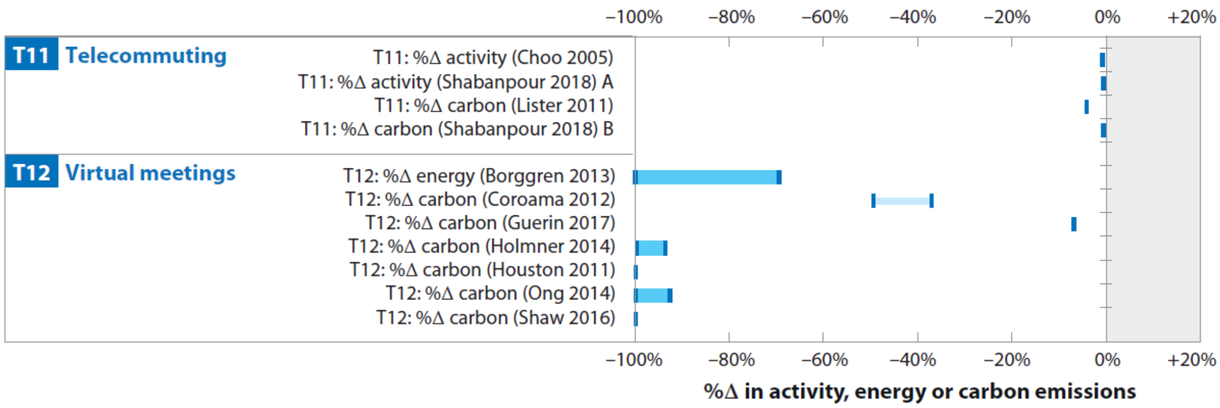


Figure 9. Transport Mobility Digital Consumer Innovations Reviewed in Wilson et al. 2020
Source: Wilson et al. 2020

Similar to Wilson et al. 2020, the review in Ivanova et al. 2020 also focused only on passenger (and not freight) transport innovations, but still found that transport sector had the highest mitigation potential compared to other domains. Within passenger transport innovations, reducing car and air travel had the greatest energy and related CO_2 emissions reduction potential, followed by shifts toward less carbon-intensive fuels and modes of transport (Figure 10). More specifically, Ivanova et al. 2020's review identified substantial mitigation potential associated with reducing air travel, on the order of reducing 0.7 – 4.5 tCO_2e/cap for every long-haul return trip avoided, with strong corresponding relationship between reduction potential and income. Living car-free has the highest median CO_2 mitigation potential, but the potential ranges from 0.6 to 3.6 tCO_2e/cap depending on assumptions about vehicle and fuel characteristics. More limited energy and CO_2 reduction potential was identified for mode shifting to public transit and active modes, with 0.6 to 1 tCO_2e/cap reduction possible from replacing short-distance urban car trips. Ivanova et al. 2020 also included fuel switching to hybrid, electric and fuel-cell vehicles in its review, but identified a wide range in CO_2 mitigation potential. The wide range resulted primarily from different grid fuel mixes used in different studies, which accounted for as much as 70% variability in life-cycle analysis results. Notably different from Wilson et al. 2020 is that Ivanova et al. 2020 did not consider substitution or induced demand effects in its review, and increases in CO_2 emissions from transport innovations were due to changes in grid fuel mix, not due to activity changes.

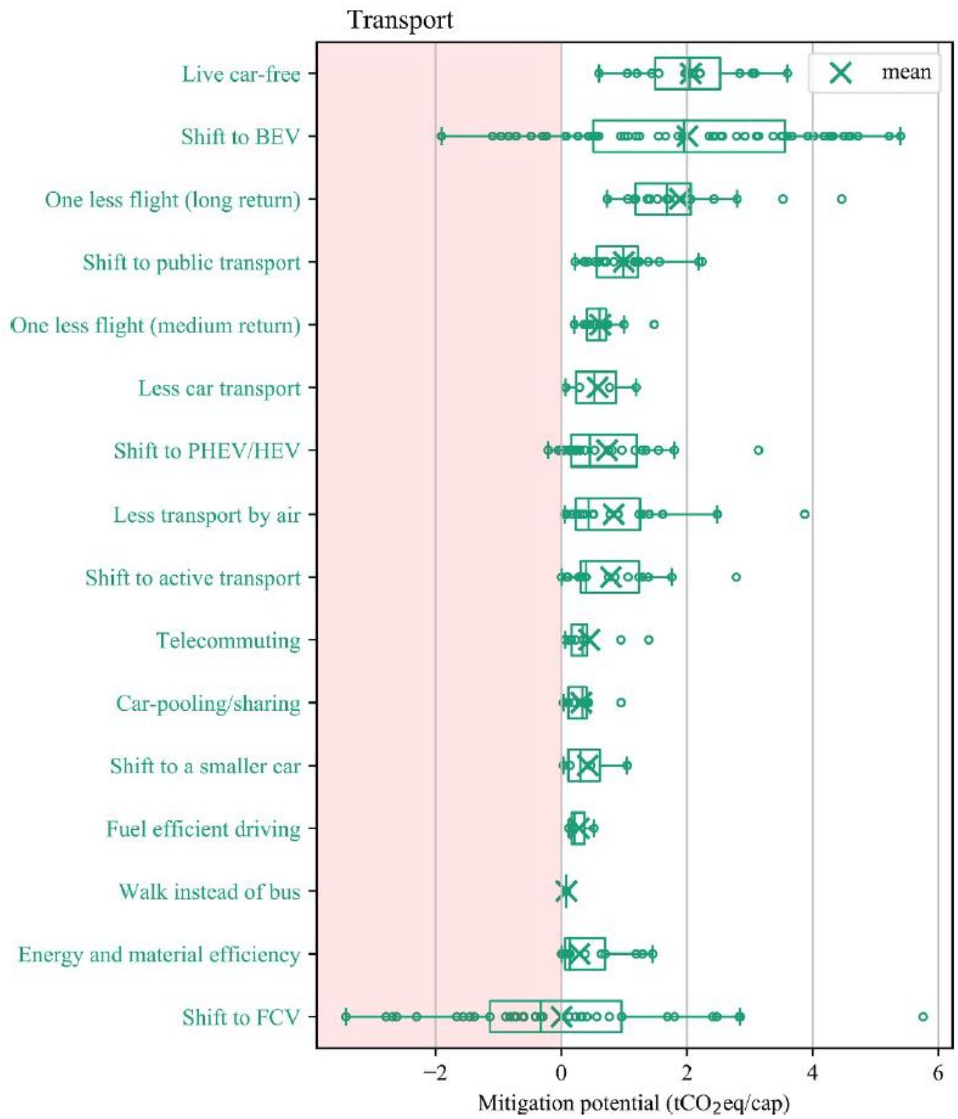
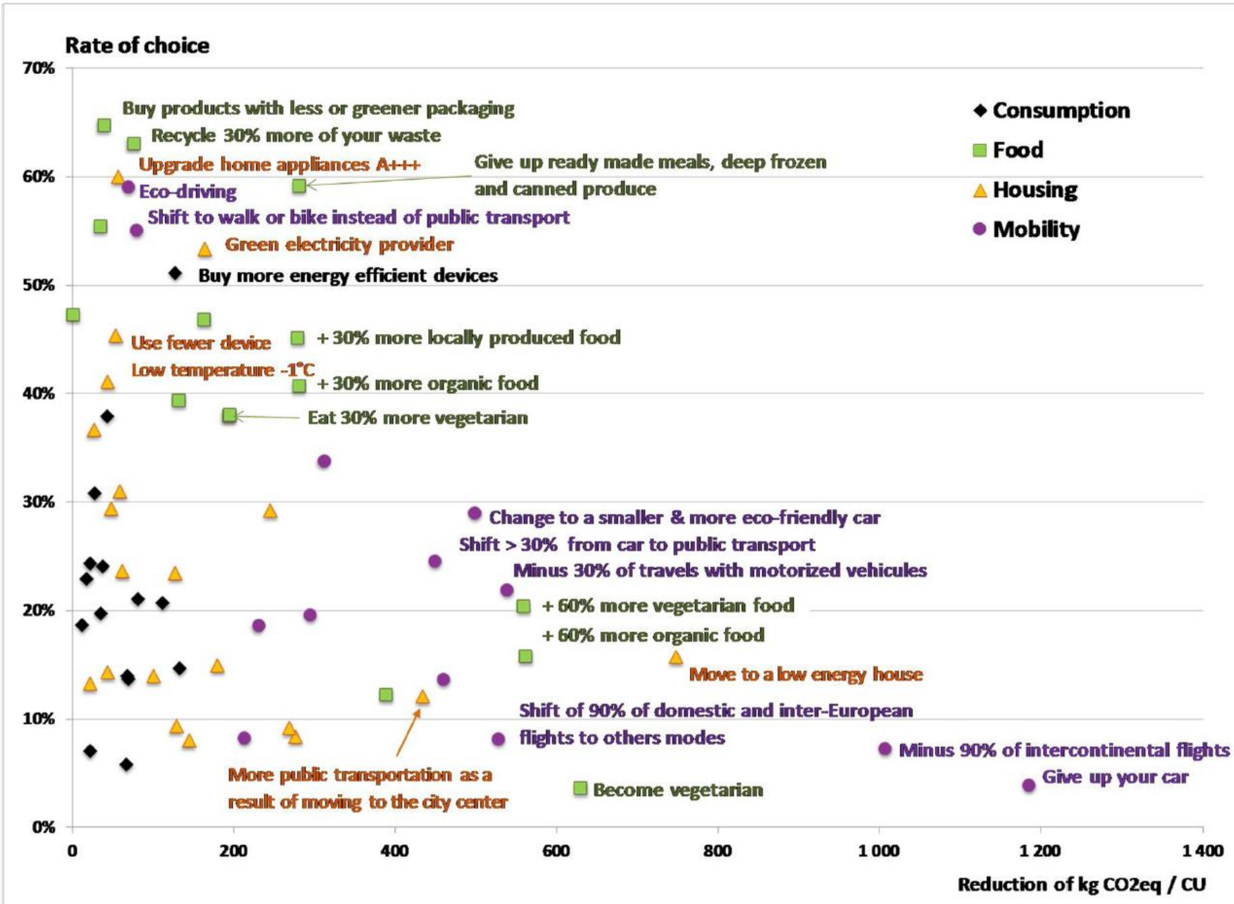


Figure 3. Annual mitigation potential of consumption options for transport measured in tCO_2eq/cap. The figure is based on a sample of 23 review articles and 16 consumption options. Negative values (in the red area) represent the potential for backfire. The dots represent single reviewed studies and the x–s—the average mitigation potential within the same consumption option. The 25th percentile, median and 75th percentile are noted with lines, with the options ordered by medians. The supplementary spreadsheet sheet contains an overview of all options. For transport, we adopted the estimate of 15 000 km per passenger per year in the OECD [61], 1000 km in China [62] and 24 000 km in the USA [62, 63] for studies which do not specify annual travel.

Figure 10. Annual Mitigation Potential of Transport Consumption Options in Ivanova et al. 2020
Source: Ivanova et al. 2020

Dubois et al. 2019's analysis was based on feedback from households that participated in designed mitigation selection "game" using information provided on CO_2e savings, financial costs and health impact when relevant, with follow-up qualitative interviews with households on decision choices. In contrast to the high reduction potential identified in the two other studies, Dubois et al. 2019 found that households were less willing to take actions to reduce CO_2 emissions voluntarily in the transport sector, compared to other sectors. For transport, voluntary actions chosen by most households include fairly incremental efficiency improvements through eco-driving, shifting to active modes, and purchasing more eco-friendly (e.g., smaller) cars with lower CO_2 mitigation potential (Figure 11). In contrast, households were less willing to give up private cars and reducing intercontinental flights, especially for those households that have taken recent flights, despite having received information that these actions have greater CO_2 reduction potential.



Note: Each symbol represents one mitigation action. The *x*-axis shows how much reduction of CO_2e an action yielded for households (per consumption unit) on average. The *y*-axis shows the percentage of households that chose an action in the voluntary scenario. The colors correspond to the four different categories of consumption (food, mobility, housing, and other consumption). The reference of 100% are those households that were able to choose the specific actions. For instance, 128 out of all 308 households had used intercontinental flights at baseline. 10 of those 128 chose the action *reduce your intercontinental flights by 90%*. Thus, the action was unpopular and is found on the lower part of the panel. At the same time, the action is placed on the right side of the panel, as it yielded a large of CO_2e reduction per capita of about 1000 kg.

Figure 11. Household Preferences for Mitigation Options and CO2 Reduction Potential from Dubois et al. 2019

Source: Dubois et al. 2019

The contrast between the findings from household preference surveys from Dubois et al. 2019 with reviews of published studies in Wilson et al. 2020 and Ivanova et al. 2020 leads to several notable findings. Avoid measures that reduces passenger transport activity, particularly those related to not using automobiles and not flying, have the largest mitigation potential but are also the most difficult to quantify and to achieve. They are difficult to quantify due to counterfactual baselines or reference points, and substitution and induced demand effects that are difficult to model and capture. Achieving the potential savings in reality is also difficult because there is less willingness for individuals (particular those with higher incomes and tendencies to consume) to change their consumption patterns, in part due to personal and cultural values attached to mobility. Telecommuting, eco-driving, and shifting to active modes have moderate reductions in energy and related CO_2 emissions, but are more likely to be adopted voluntarily.

2.3.2 Comprehensive Transport Scenario Case Study

The review studies covered in the previous section analyzes and compares the impacts of individual transport innovations on energy demand and related CO_2 emissions, but did not evaluate the combined impacts of multiple transport innovations on reducing total transport energy demand and emissions. As introduced in previous work, modeling scenarios based on narratives or scenario storylines is one methodological approach to modeling technological and social innovations' potential impact on reducing energy demand and related emissions (Khanna et al., 2021). For transport specifically, Dillman et al. 2021 represents a case study of how direct and indirect GHG emissions scenarios were developed to model the impact of comprehensive sets of avoid, shift and improve passenger transport strategies for the Icelandic capital city of Reykjavik. As seen in Figure 12, the avoid, shift and improve framework is used to evaluate different strategies for reducing transport demand through different modeling parameters based on the Kaya identify for direct emissions, and linked to roles for government, individuals and businesses.

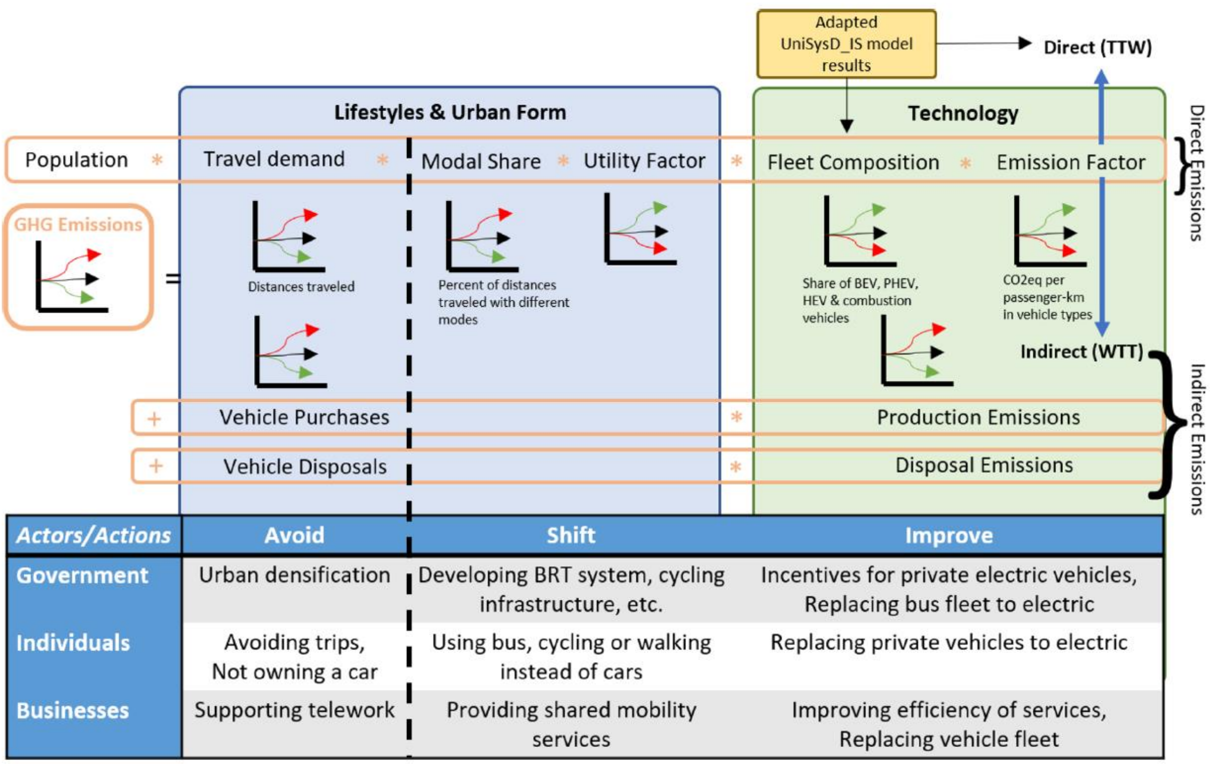


Figure 12. Modeling Parameters for Direct and Indirect Estimations for a Transportation Sector in Dillman et al. 2021

Source: Dillman et al. 2021

Narrative scenarios were developed in Dillman et al. 2021 to represent different combinations of technological and social innovations that included:

- Urban structural change + lifestyle changes, including urban densification as reflected by mode shifting to active or public transit, avoided car ownership, and increased telecommute
- Technological change: electrification, digitalization, mobility as a service

- Integrated approach encompassing urban structural change, lifestyle changes and technological change
- Radical social change: strong reduction of travel demand, support and uptake of mobility as a service and transit, shifts in norms for car-less lifestyles

As seen in Figure 13, these scenarios span the 2-axis behavioral/urban form and technological changes framework.

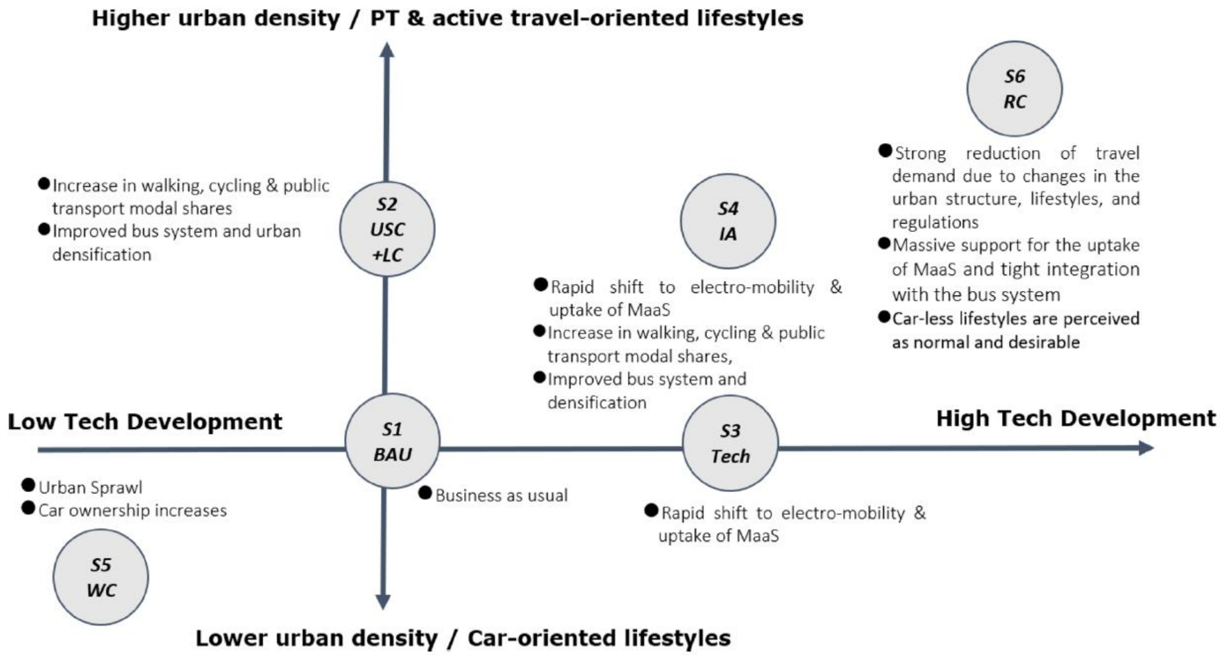


Figure 13. 2-axis Framework for Scenarios of Behavioral/Urban Form and Technological Changes to Transport in Dillman et al. 2021

Source: Dillman et al. 2021

Dillman et al. 2021's scenario analysis found that integrated approach of e-mobility through technologies, collective or shared transport and low-mobility societies through structural and lifestyle changes can lead to the most significant reductions in annual and cumulative direct and indirect GHG emissions, when Reykjavik's relatively decarbonized grid is considered. It also highlights the importance of considering indirect emissions associated with life-cycle emissions of vehicles as well as vehicle fuels, in addition to direct operational emissions.

2.3.3 Case Studies of New Urban Transport Innovations

This section focuses on case studies of new transport technological and/or social innovations that were not included in previous work and are based on the latest studies that have been published. For each innovation case study, we review what the latest innovation is and how it is expected to affect transport activity, energy demand and/or GHG emissions based on survey data or simulation modeling.

2.3.3.1 Micromobility

In urban areas, an emerging innovation in passenger transport that could reduce energy demand and related CO_2 emissions is the concept of micromobility. Although there is no specific consensus on how to define micromobility, the term generally refers to small and lightweight modes of transport with low travel speeds of less than 25 kilometers per hour, and often powered with an electric powertrain. Common examples of micromobility vehicle traditional non-motorized bicycles, electric powered bicycles (e-bikes), electric standing scooters (e-scooters), and electric seated scooters (Sun et al. 2021). Micromobility is typically used in urban areas as complementary or supplementary modes of transport for commuting, or for leisure and recreational travel. Existing studies of micromobility trends and impacts have focused on the U.S., Europe, Canada, United Kingdom, New Zealand, and China (Sengul and Mostofi, 2021).

A recent literature review of micromobility studies found that although it can be used for trips of less than 8 kilometers, the average number of trips per day varied significantly between cities, ranging from 0.8 to 1.4 trips per day (Sengul and Mostofi, 2021). For e-scooters, a common form of micromobility, the distance travelled from reviewed literature was mostly around or under 2 kilometers per day with an average duration of 8 to 12 minutes per trip. However, one pilot project in the German city of Munich reported a much higher travel distance of 11 kilometers per day (Sengul and Mostofi, 2021). Recent studies have also reported increased use of e-scooters for traveling longer distances during the global Covid-19 pandemic. Analysis have found that e-scooters are highly cost-effective, with a short payback period of only 4 months and are the most cost-effective vehicles for short-distance travel (Sengul and Mostofi, 2021).

Another common form of micromobility is e-bikes, which were used for a longer average distance of 3 to 4.5 kilometers and average 15 to 20 minutes of travel time, However, there is large variations in reported travel distance between cities and studies ranging from 1.6 kilometers in Zurich to 11.4 kilometers in the Chinese city of Kunming (Sengul and Mostofi, 2021).

In terms of energy impact, micromobility vehicles can reduce direct energy consumption through mode shifting from passenger cars (e.g., private cars or taxis) to smaller mobility forms that are much more efficient. As seen in Table 5, the energy intensities per kilometer travelled or passenger-kilometer for micromobility vehicles are much lower than for driving. This is true even after taking into consideration additional rebalancing energy consumption per trip for shared micromobility programs. However, the net energy impact of shifting to micromobility is closely related to the mode and type of trip that is being replaced. For examples, surveys of micromobility users found that 20% to 30% of respondents and up to half of tourist respondents would have used cars or taxis, ride hailing services such as Uber or Lyft in major U.S. cities of Portland, San Francisco, Denver, Chicago and Raleigh. In France, however, walking and public transport were reported as the most common alternatives to micromobility (Sengul and Mostofi, 2021).

Table 5. Vehicle and Rebalancing Energy Intensities of Common Forms of Micromobility

	Vehicle energy intensity		Rebalancing Energy per Trip		Source
E-scooter	0.012 - 0.040	kWh/km travelled	N/A		Sengul and Mostofi, 2021
Driving	0.560	kWh/pass-km	0		Sun et al. 2021
Transit	0.410	kWh/pass-km	0		Sun et al. 2022
E-bike	0.014	kWh/pass-km	0.1136	kWh/trip	Sun et al. 2023

E-scooter	0.017	kWh/pass-km	0.0041	kWh/trip	Sun et al. 2024
Seated scooter	0.065	kWh/pass-km	0.1136	kWh/trip	Sun et al. 2025

Note: values from Sun et al. converted from kWh/passenger-mile to kWh/passenger-kilometer

To better understand the nuanced potential impacts micromobility, particularly shared micromobility programs, may have on transport energy consumption, a U.S.-focused study used national and city-level data to analyze energy bounds for the adoption of shared micromobility. Using scenario analysis and detailed travel data, Sun et al. 2021 modeled different levels of shared e-bike and e-scooter adoption for short trips and access/egress from existing transit to understand the energy impacts of different adoption levels. It also modeled the additional energy consumption of rebalancing shared micromobility, as seen in Table 5. Sun et al. 2021 found that at peak adoption, micromobility have energy bound of 0.96% decrease to 0.1% increase of total energy consumed across all passenger trips at the national level. When city-level data for the California city of Sacramento is used, Sun et al. 2021 found energy bounds of 2.6% decrease to 0.2% increase in total energy consumed across all passenger trips within city associated with the adoption of shared micromobility. Similar to other mode shifting strategies, the net increase or decrease in energy consumption resulting from shared micromobility is highly dependent on the type of trip (e.g., motorized versus non-motorized) being replaced by the e-bike or e-scooter. Sun et al. 2021 also found that e-bikes showed the greatest energy savings potential due to longer distance travel and ability to serve a greater number of micromobility-feasible trips while e-scooters have more limited applications.

2.3.4 Car-sharing replacement of private car ownership

As discussed in Khanna et al. 2021, how car-sharing systems are designed can potentially lead to reduced use of private cars. Free floating car sharing is a common business model that is more dynamic and spontaneous, where a commercial fleet of cars is provided within a designated area and used following an hourly or distance-based fee. This type of car sharing system has been on the market for more than 10 years and growing rapidly in recent years, including serving over 3 million users in 16 cities and 8 countries in Europe in 2020 (Jochem et al. 2021). A recent analysis by Jochem et al. 2021 based on user surveys in 11 European cities from 2018 to 2019 found that 3.6% to 16% of respondents reported having sold a car after participating in a free-floating car sharing program, with 2.1 to 5.3 users per shared car indicating they have sold a car. The study identified multiple factors that may have contributed to decreases in car ownership, including: travel patterns and use of car-sharing programs, local geographic conditions, and cost-savings. Users showed a greater probability of selling a car if they drove longer mileage and used shared car more frequently, or have membership in car-sharing for a longer time. City-specific characteristics that impacted car-sharing and car ownership included: public transport infrastructure or limited parking spaces, local societal attitude on vehicle ownership, car-sharing fleet size and density, and the existence of driving bans or low emission zones in city centers. Lastly, users also cited the cost-savings from shedding a car by avoiding the fixed cost of car ownership as a key reason for replacing car ownership with car-sharing (Jochem et al. 2021).

2.4 Cross-sector

Two additional cross-sector innovation have been added for Year 2: Personal carbon trading and digital innovation.

2.4.1 Personal carbon trading

Personal carbon trading (PCT) is a carbon emissions cap-and-trade system similar to that used for business or industries. Carbon emissions are allocated as credits ("cap") to individual households in order to regulate consumption of fuel and energy; these credits can be bought and sold between individuals ("trade"). This ability to trade allows for a more effective method of passing the external costs of high-carbon lifestyles (resulting in emissions which contribute to negative environmental, social, economic, and health consequences) onto households that choose to pay (through buying carbon credits) to emit more.

Most high-income countries have a per capita energy consumption of between 30-80,000 kWh per year (BP, 2020). The majority of energy used by individuals is on personal level through transportation, heating/air conditioning, and water heating, for example. Indirect uses of energy come from food or clothing production. For example, food production, transport, and storage accounts for 12% of the US's national energy budget, while 4.7 kg of CO_2 is emitted per capita per day, just for food (Center for Sustainable Systems, 2021). Global clothing production contributes to 10% of annual global carbon emissions and are expected to increase by over 50% by 2030 (World Bank, 2019).

The original design for PCT encompasses around 40% of carbon emissions (in high-income countries) relating to energy usage from travel, heating/air conditioning, water heating, and household electricity consumption (Nerini et al., 2021). PCT allots carbon allowances according to carbon reduction targets set by each country (the UK, for example, aims to reduce 80% of personal carbon emissions between 1990-2050 in a legally binding agreement) (Fan et al., 2016). It has been estimated that the full implementation of this PCT scheme could reduce CO_2 emissions by up to 25% within 10-15 years based on pre-COVID estimates (Nerini et al., 2021). This suggests PCT can be an effective method of getting closer to global temperature increase limit goals, and can significantly contribute to global emissions reductions from regions with high levels of energy consumption (e.g., U.S., EU, China, India, Japan, and others).

In the building sector, PCT can be realistically implemented through "smart home" systems in high-income countries, using machine learning technology and working in conjunction with electricity and heating providers to monitor energy consumption. However, existing challenges include a lack of infrastructure needed to track the energy consumption of every individual household nationwide. In lower income countries, there is the additional challenge of not having sufficient skilled labor, financial resources, and materials necessary to install such smart home systems.

In order for PCTs to work, respect for individual privacy concerns and transparency with consumers has been found to be very important; carbon allocations (especially in initial phases) need to be reasonably feasible without major lifestyle changes and people need real-time information on how much of the allocated carbon credits the have already used. Keeping track of the carbon emissions of personal behaviors, such as personal goods and services purchased and mode of transport chosen, is also a challenge. Thus, the carbon allowance allocation must be easily updatable to allow for these discrepancies in recorded versus actual carbon footprints.

Another major barrier to implementation is political support and enforcement at national and local lelves, and international coordination on setting caps and emission credit pricing. In order to gain public and political acceptance of PCT, the participation and leadership of high-emissions countries in adopting PCTs will be needed for public and widespread political acceptance at the global level. In addition, collaboration on a global scale on setting carbon caps and emission credit pricing that are appropriately scaled to each country's GDP and their citizens' willingness to participate in the PCT scheme is another key factor. Adopting PCT also affects the availability and prices of products and services produced by any companies compliant with the carbon allocation scheme.

A personal carbon trading scheme was implemented in Shenzhen, China in 2021 through a voluntary incentivized digital pilot called “Low Carbon Planet.” Emission reductions of individuals taking public transport systems were digitally recorded through their smartphones and accumulated as carbon credits. Through this platform, individuals could also trade credits accumulated by making low-carbon consumption choices and under-emitters were financially rewarded with money from individuals who chose to purchase more carbon credits (Dong, 2021). This pilot showed that it was technologically feasible to digitally track individuals’ carbon emissions through their methods of transportation and credit card transactions. Because this pilot was voluntary, however, the actual scope of energy demand reduction could not really be captured; those who chose to participate were mainly individuals who were already conscientious of their carbon footprint.

Another recent PCT scheme was implemented in Lahti, Finland in 2021 through the CitiCAP app. The scheme was free and voluntary to join and encouraged users to lower their carbon emissions through alternative modes of transportation. Whenever users were logged as walking or biking instead of driving, they were awarded “virtual coins” which could be traded to purchase tickets to swimming halls, local buses, and more (Urban Innovative Actions, 2021). It also provides up-to-date information to users on their personal carbon footprints.

There are two theories as to the costs of implementing PCT schemes. Firstly, if individuals’ carbon accounts are run through their banking accounts, Dresner’s 2005 study estimates the set-up costs to be £50–100 million and the annual running costs (mainly for managing data and the digital infrastructure) to be around £50 million. Lockwood’s 2009 study estimates the annual running costs to not exceed £250 million. As for Lane et al.’s 2008 study, which considers that some people do not have bank accounts, they estimate that the set-up costs could be between £0.7–2 billion and the annual running costs between £0.7–1.8 billion. However, Lane et al.’s estimated costs are much higher than all other studies. These studies estimated that the largest cost of running a nationwide PCT scheme would be posting the monthly report of carbon usage; these studies, however, are dated in 2022. Online automated reports of carbon usage would be significantly more cost-effective and online banking is widely accessible in all high emission countries (with the exception of certain rural areas of India and possibly China, although the carbon emissions of individuals in rural areas is somewhat negligible). For the individual’s cost to engage in PCT, the Institute for Public Policy Research (IPPR) estimates it to be around £10–15 a year with about 2 hours of annual engagement for individuals who do not participate in large scale carbon trading (Starkey, 2012).

The allocation of carbon allowances is a very decisive topic that primarily must be set according to each country’s electricity consumption per capita and aim at reducing the resulting emissions. In order for a nation-wide PCT scheme to achieve success, it is estimated that it must have at least 80% public acceptance (as opposed to 70% for corporate cap and trade in areas of the EU) (Starkey, 2012). To garner public support and ensure moderate levels of equity, the carbon allocation of households with children and extra needs (e.g., medical or lack of stable income) must be slightly adjusted. PCT can provide a buffer between the energy price and allowance price. When the energy price rises, the carbon allowance price will fall, and vice versa. Thus, the total price of energy remains stable. With decreased emission rates, the welfare loss of the over-emitter will decrease; however, the welfare change is still negative and far less than zero (Fan, 2015).

Overall, with public and political support, PCT has major energy demand reduction potentials. PCT, unlike blanket carbon taxation, does not just increase costs for high carbon consumption (a policy that only restricts the consumption of low-income households), but also provides a definitive cap on nation-wide personal carbon emissions. High income households are blocked from immensely over-emitting because of the finite amount of carbon credits that are allocated; if there are no more credits to purchase from other households, they simply must emit less or face large penalties that are not just restricted to monetary fines.

The PCT model stimulates money flow from over-emitters to under-emitters and from the wealthy to the poor. It provides economic, political, and social incentives for high-income consumers to invest their money in more efficient technology and energy usage in order to pay less for additional carbon credits and provide tax breaks. On the social side, PCT schemes increase the visibility of personal carbon footprints due to everyday consumption and individuals' impacts on the environment. With a successful PCT scheme, social and cultural norms will begin to shift and favor lower emission lifestyles and gradually reduce demand for carbon-intensive goods, services, and energy providers.

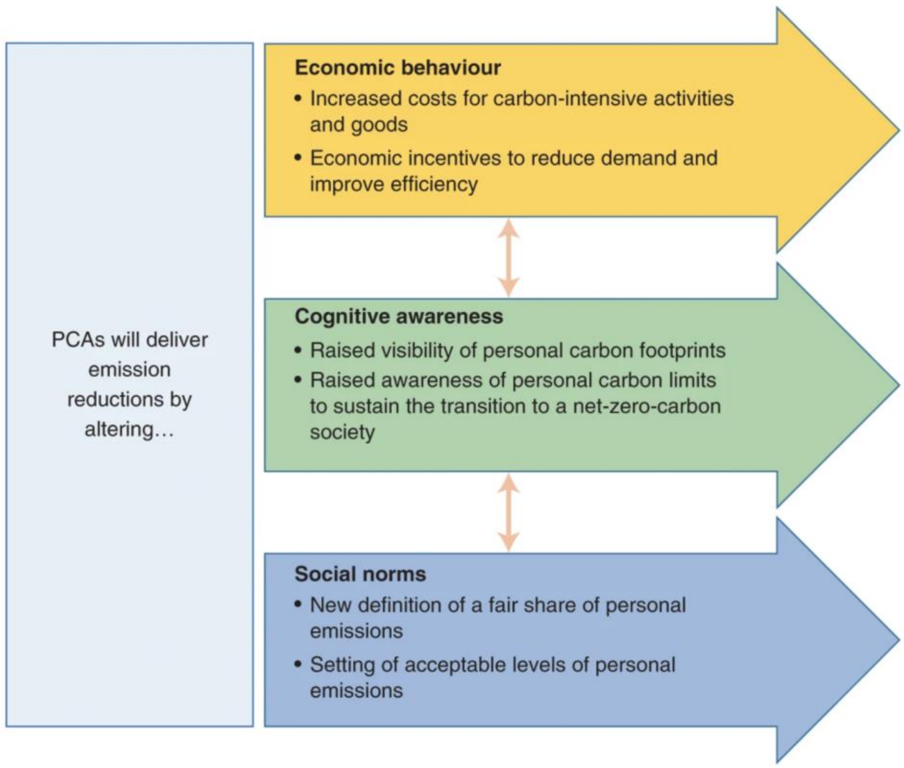


Figure 14. Impacts of Personal Carbon Allowances
Source: Nerini et al. 2021

2.4.2 Digital Innovations in Influencing Lifestyle Choices

As seen in Shenzhen's PCT pilot, digital innovation is essential in reducing individuals' CO_2 emissions and energy demand by providing accurate, accessible, and up to date information on their carbon footprint and creating both social and economic incentives for reducing emissions.

One digital program designed to encourage and incentivize low-emission lifestyles is the Ant Forest scheme in China launched by Alipay, a platform with over one billion users. Users are awarded "green energy points" for making environmentally sustainable lifestyle and consumer decisions such as reducing carbon emissions through transportation or electricity consumption or purchasing from environmentally-friendly brands. The Ant Forest scheme uses games (e.g., competing with peers) and incentives to increase users' engagement with earning green energy points. These points contribute funds towards planting trees or protecting land for conservation efforts (in conjunction with environmental NGOs) in China.

As of 2020, over 500 million members were involved in the Ant Forest scheme for adopting lower-carbon lifestyles (UNFCCC, 2022). When these plants grow up, the cumulative carbon reduction exceeds 12 million tons and the gross ecosystem product provided by the Ant Forest scheme is predicted to reach 11.18 billion RMB (Zhang et al., 2021). In addition to land protection, tree planting, carbon sequestration, and emissions reductions, the Ant Forest scheme has thus far created 400,000 jobs in Inner Mongolia, Gansu and other provinces, and contributed to an increase of over 100 million RMB in labor services (Zhang et al., 2021). As for the trading potential of these green energy points, a total of 8.943 million tons of carbon quota was traded in 2018 by the Beijing Environment Exchange, with a year-on-year increase of 18.83% (Zhang et al., 2021). This demonstrates the feasibility and willingness to participate in a future carbon trading market in China (including the implementation of personal carbon trading).

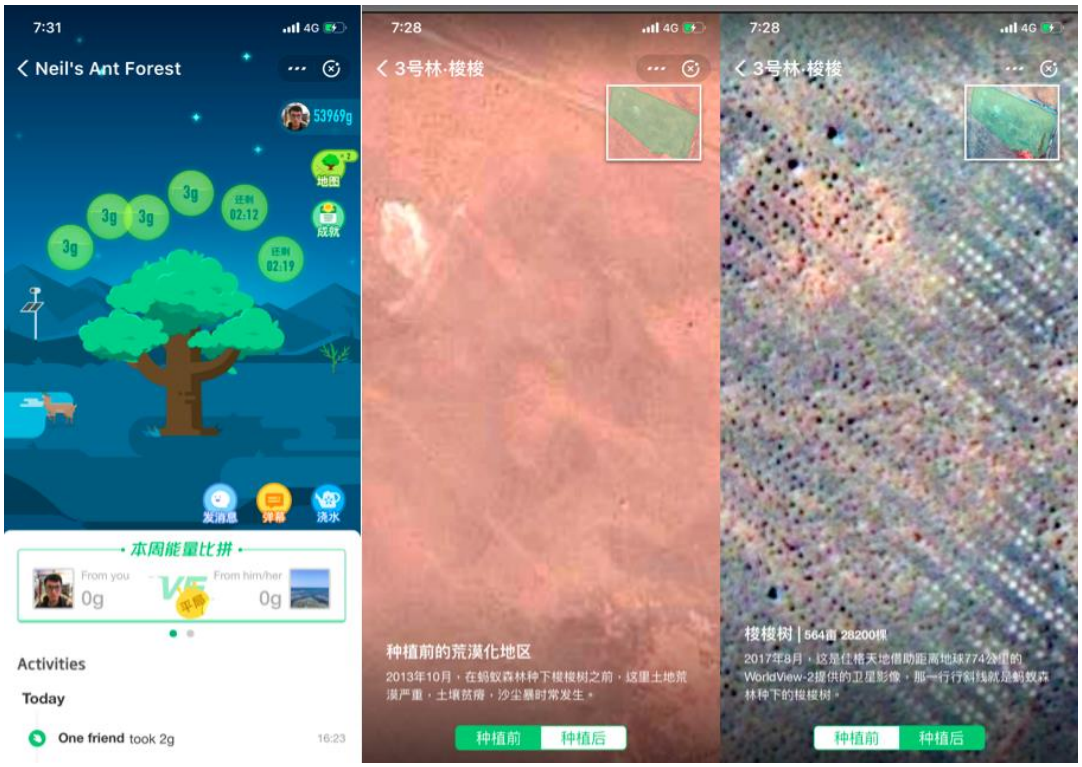


Figure 15. AntForest Images

Source: https://www.alizila.com/how-alipay-users-planted-100m-trees-in-china/

Google also announced new features in 2021 to help consumers make more sustainable lifestyle choices. The new services focus on reducing GHG emissions through its applications in Google Search, Maps, Travel, and Nest.

For example, when shopping on Google, eco-friendly products (specifically cars and energy-efficient home appliances) will be prioritized towards the top of search results, making it easier for individuals to find and purchase these products. On Google Maps, individuals will be able to see the most fuel-efficient routes, which is also planned to become the default route in 2022, so consumers can save fuel consumption and also make more low-emissions transport choices. There have also been updates to the walking, bicycling, and public transportation information on Google Maps to make it more convenient and encouraging for individuals to choose these low-emission mode options. Google Travel will show consumers their exact carbon footprint based on their airplane travel route searches, specific to the exact airplane seat they choose, so they can make more informed decisions related to flying.

Google's service for Nest thermostats in the US allows users to automatically shift their heating and cooling loads to times when there is more renewable energy available for use on the grid. This is a strategy endorsed by energy experts as a strategy to make homes more energy efficient and reduce strain on the electricity grids during times of peak demand.

These new digital services provide two avenues of reducing energy consumption by individuals. The first is information visibility/awareness; when people are able to see their exact carbon footprints due to transportation or heating (the two main sources of energy consumption on an individual level) they will be more likely to decrease their energy consumption, especially for households with medium energy consumption levels. The second is not just convenience but information dissemination; by providing low energy alternatives directly under the fingertips of consumers, it makes it more likely and appealing to choose these alternatives.

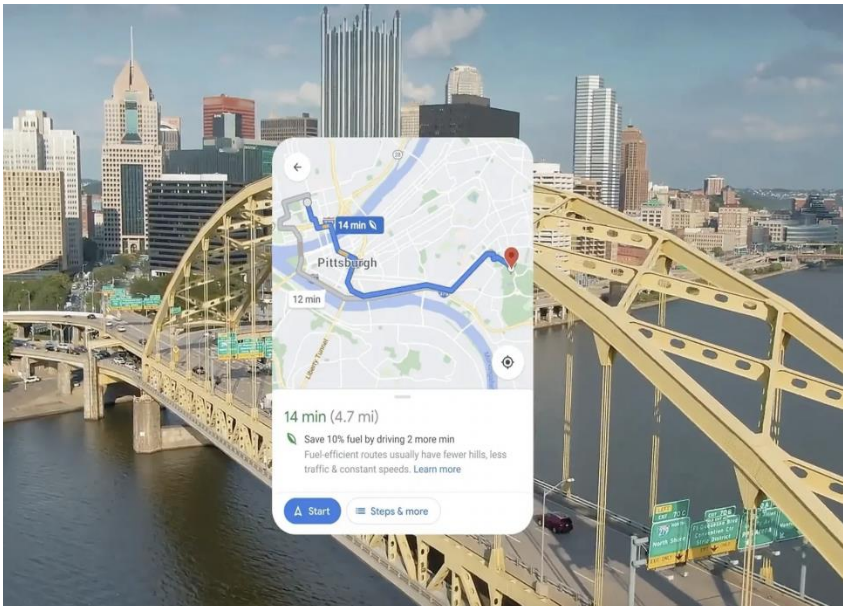


Figure 16. Example of Google Map Feature on Highlighting Fuel-efficient Routes

Source: https://www.theverge.com/2021/10/6/22711623/google-climate-change-greenhouse-gas-emissions-carbon-footprint-maps-search-travel

3. Assessment of Role for Technological and Social Innovations on Energy Demand Side in Recent Carbon Neutrality Reports

In the last few years as countries prepared to submit their revised Nationally Determined Contributions to the 26th United Nations Climate Change Conference of the Parties (COP26), more countries and regions have announced carbon neutrality targets and/or released carbon neutrality roadmaps analyze if and how carbon neutrality can be met by mid-century or later. These include a global net-zero roadmap released by the International Energy Agency (IEA), national net zero roadmaps or climate action plans for European countries including the United Kingdom, France and Germany, and an IEA net zero roadmap for China. Some of these roadmaps have analyzed if and how lower energy demand due to cross-sector and sector-specific technological and social innovations can contribute to meeting carbon neutrality targets. In this section, we assess and review which technological and/or social innovations are included in existing carbon neutrality roadmaps, and any explicit assumptions about the adoption of these innovations over time. By understanding how technological and/or social innovations' potential energy and emissions impacts are assessed either qualitative or quantitatively, this review highlights their potential roles in and contributions to meeting carbon neutrality targets. These existing roadmap examples also provide insight on how existing global models and scenarios have considered the impact of technological and social innovations on energy demand to inform national carbon neutrality planning, and potential policy implications.

3.1 International Energy Agency (IEA)'s 2021 Net Zero by 2050 Global Roadmap

In IEA's 2021 *Global Net Zero by 2050: A Roadmap for the Global Energy Sector,* technological and social innovations intended to reduce energy consumption and/or related emissions were collectively considered as mitigation measures grouped as "behavioral change" in its Net-Zero Emissions by 2050 (NZE) Scenario. More specifically, the scoping of behavior change measures is narrowly defined as ongoing or repeated behavior, and excludes one-time action such as one-time adoption of a new technology. The ongoing or repeated behaviors include three main types: voluntary changes to reduce excessive or wasteful energy use (primarily applicable in buildings and transport sectors), transport mode switching, and material efficiency gains in industry.

As a global roadmap study, the assumed scope, scale and speed of adoption of different behavior change measures vary across regions under the NZE scenario, depending on different factors that include the availability of existing or new infrastructure to support changes, geographical and climatic conditions, urbanization trends, and social norms and cultural values. However, significant behavior changes with the potential for reducing energy consumption and related CO_2 emissions are expected at a global scale, as shown in Table 6 below in terms of intermediate milestones by sector and measure.

Table 6. IEA 2021 Net Zero by 2050 Global Roadmap Milestones for Behavior Change in the NZE Scenario

Sector	Year	Milestone
Industry	2020	• Global average plastics collection rate = 17%.
	2030	• Global average plastics collection rate = 27%. • Lightweighting reduces the weight of an average passenger car by 10%.
	2050	• Global average plastics collection rate = 54%. • Efficiency of fertiliser use improved by 10%.
Transport	2030	• Eco-driving and motorway speed limits of 100 km/h introduced. • Use of ICE cars phased out in large cities.
	2050	• Regional flights are shifted to high-speed rail where feasible. • Business and long-haul leisure air travel does not exceed 2019 levels.
Buildings	2030	• Space heating temperatures moderated to 19-20 °C on average. • Space cooling temperatures moderated to 24-25°C on average. • Excessive hot-water temperatures reduced.
	2050	• Use of energy-intensive materials per unit of floor area decreases by 30%. • Building lifetime extended by 20% on average.

Note: Eco-driving involves pre-emptive stopping and starting; ICE = internal combustion engine.

Source: IEA, 2021

In terms of impact, IEA's NZE scenario found that 63% of the emissions reductions under the NZE scenario can be attributed to some form of involvement with consumers. This includes 8% of emissions reductions being attributed directly to behavior change and material efficiency gains, and an additional 55% reduction form a mix of technology deployment and active involvement or engagement with consumers, such as in fuel switching (IEA, 2021). In terms of behavior change measures described above, it was found to reduce energy activity by 10-15% annually, with annual global energy reduction potential of 37 exajoules in 2050 (IEA, 2021). In 2030, this translates into 1.7 GtCO2 emissions avoided, with 45% of the reductions coming from transport and 40% from industry. For transport, key measures include decreasing car ownership through shifting of 20-50% car trips to buses, and the remainder to cycling, walking and public transport in big cities, improved fuel economy, and assuming behavior change can stabilize demand for business air travel and long-haul leisure travel at 2019 levels. For aviation, behavior change in reducing demand for aviation and shifting 17% of regional flights to high-speed rail by 2050 together can reduce aviation CO_2 emissions by half by 2050 (IEA, 2021). For industry, key measures contributing to CO_2 emissions reduction include reducing waste and improving the design and construction of buildings. By 2050, most of the annual 2.5+ $GtCO_2$ emissions reductions associated with behavior change will be from industry as transport and building sectors are highly electrified.

In addition to modeling and quantifying the potential energy reductions and CO_2 emissions impacts of the behavior change measures considered in its NZE scenario, the IEA study also qualitatively assessed the measures in terms of their compatibility with possible policy options (see Table 7). Further analysis found that regulations and mandates would be needed to enable 70% of the modeled emission reductions, along with new or re-directed investment in support infrastructure (IEA, 2021). Market-based instruments can help enable two-thirds of the modeled emissions reductions for behavior change under the NZE scenario, while information and awareness measures alone can only enable 30% of the emissions reductions. It also recognized that individual citizens and companies play equal role in enabling behavior change (IEA, 2021).

Table 7. IEA 2021 Net Zero by 2050 Global Roadmap's Key Behavioral Changes in the NZE Scenario and Policy Implications

	Policy options	Related policy-goals	Cost-effectiveness	Timeliness	Social acceptability	CO_2 emissions impact
Low-car cities • Phase out ICE cars from large cities. • Rideshare all urban car trips.	• Low-emissions zones. • Access restrictions. • Parking restrictions. • Registration caps. • Parking pricing. • Congestion charges. • Investment in cycling lanes and public transportation.	• Air pollution mitigation. • Public health. • Reduced congestion. • Urban space. • Beautification and liveability.	🟡	🟡	🟡	🟢
Fuel-efficient driving • Reduce motorway speeds to less than 100 km/h. • Eco-driving. • Raise air conditioning temperature in cars by 3 °C.	• Speed limits. • Real-time fuel efficiency displays. • Awareness campaigns.	• Road safety. • Reduced noise pollution.	🟢	🟢	🟡	🟢
Reduce regional flights • Replace all flights <1h where high-speed rail is a feasible alternative.	• High-speed rail investment. • Subsidies for high-speed rail travel. • Price premiums.	• Lower air pollution. • Lower noise pollution.	🔴	🔴	🟡	🟡
Reduce international flights • Keep air travel for business purposes at 2019 levels. • Keep long-haul flights for leisure at 2019 levels.	• Awareness campaigns. • Price premiums. • Corporate targets. • Frequent-flyer levies.	• Lower air pollution. • Lower noise pollution.	🟢	🟢	🟡	🟢
Space heating • Target average set-point temperatures of 19-20 °C.	• Awareness campaigns. • Consumption feedback. • Corporate targets.	• Public health. • Energy affordability.	🟢	🟢	🟢	🟢
Space cooling • Target average set-point temperatures of 24-25 °C.	• Awareness campaigns. • Consumption feedback. • Corporate targets.	• Public health. • Energy affordability.	🟢	🟢	🟢	🔴

🔴 = poor match 🟡 = neutral match 🟢 = good match

Notes: Large cities = cities over 1 million inhabitants. ICE = internal combustion engine. CO_2 emissions impact = cumulative reductions 2020-2050. Eco-driving = early upshifting as well as avoiding sudden acceleration, stops or idling. The number of jobs that can be done at home varies considerably by region, globally, an average of 20% of jobs can be done at home.

Source: IEA, 2021

3.2 United Kingdom Roadmaps

The transition to net-zero emissions economy in the United Kingdom has been analyzed in multiple studies, including a government-sponsored "Absolute Zero Roadmap" research issued in 2019 and a recent literature review article that reviewed deep decarbonization studies from 2015 through 2020. The 2019 Absolute Zero Roadmap focused on actions or shifts by industrial sectors and individuals, with a scope that is limited to using only today's available technologies and full electrification. It assessed how the U.K. can achieve zero GHG emissions by 2050, without considering potential role of negative emissions or accounting of imports, international shipping and aviation bunker fuels. Based on this scope, the analysis found that the U.K. can achieve absolute zero emissions by 2050 by reducing current energy consumption by 60% if full electrification is achieved, and by phasing-out end-uses that cannot be electrified. At the sectoral level, the roadmap identified a number of innovations that already exist but are not widely adopted as necessary to achieving zero emissions by 2050 as shown in Figure 17. Some notable innovations included in this roadmap that were assessed in Khanna et al. 2021 include: passive design and full electrification in buildings, lighter weight and small passenger vehicles, mode shifting including stopping flying, optimized location of distribution centers and new collaborative networks for co-loading for logistical improvements; extending product lifetimes, reducing overdesign and product size, and increasing re-use (UK FIRES, 2019).

	2020-2029	2030-2049	2050 Absolute Zero	Beyond 2050
Road vehicles	Development of petrol/diesel engines ends; Any new vehicle introduced from now on must be compatible with Absolute Zero	All new vehicles electric, average size of cars reduces to ~1000kg.	Road use at 60% of 2020 levels - through reducing distance travelled or reducing vehicle weight	New options for energy storage linked to expanding non-emitting electricity may allow demand growth
Rail	Growth in domenstic and international rail as substitute for flights and low-occupancy car travel	Further growth with expanded network and all electric trains; rail becomes dominant mode for freight as shipping declines	Electric trains the preferred mode of travel for people and freight over all significant distances,	Train speeds increase with increasing availability of zero emissions electricity
Flying	All airports except Heathrow, Glasgow and Belfast close with transfers by rail	All remaining airports close		Electric planes may fly with synthetic fuel once there are excess non-emitting electricity supplies
Shipping	There are currently no freight ships operating without emissions, so shipping must contract	All shipping declines to zero.		Some naval ships operate with onboard nuclear power and new storage options may allow electric power
Heating	Electric heat pumps replace gas boilers. and building retrofits (air tightness, insulation and external shading) expand rapidly	Programme to provide all interior heat with heat pumps and energy retrofits for all buildings	Heating powered on for 60% of today's use.	Option to increase use of heating and cooling as supply of non-emitting electricity expands
Appliances	Gas cookers phased out rapidly in favour of electric hobs and ovens. Fridges, freezers and washing machines become smaller.	Electrification of all appliances and reduction in size to cut power requirement.	All appliances meet stringent efficiency standards, to use 60% of today's energy.	Use , number and size of appliances may increase with increasing zero-emissions electricity supply
Food	National consumption of beef and lamb drops by 50%, along with reduction in frozen ready meals and air-freighted food imports	Beef and lamb phased out, along with all imports not transported by train; fertiliser use greatly reduced	Total energy required to cook or transport food reduced to 60%.	Energy available for fertilising, transporting and cooking increases with zero-emissions electricity
Mining material sourcing	Reduced demand for iron ore and limestone as blast furnace iron and cement reduces. Increased demand for materials for electrification	Iron ore and Limestone phased out while metal scrap supply chain expands greatly and develops with very high precision sorting	Demand for scrap steel and ores for electrification much higher, no iron ore or limestone.	Demand for iron ore and limestone may develop again if CCS applied to cement and iron production
Materials production	Steel recycling grows while cement and blast furnace iron reduce; some plastics with process emissions reduce.	Cement and new steel phased out along with emitting plastics . Steel recycling grows. Aluminium, paper reduced with energy supply.	All materials production electric with total 60% power availability compared to 2020	Material production may expand with electricity and CCS, CCU, hydrogen may enable new cement and steel.
Construction	Reduced cement supply compensated by improved material efficiency, new steel replaced by recycled steel	All conventional mortar and concrete phased out, all steel recycled. Focus on retrofit and adaption of existing buildings.	Any cement must be produced in closed-loop, new builds highly optimised for material saving.	Growth in cement replacements to allow more architectural freedom; new steel may become available.
Manufacturing	Material efficiency becomes prominent as material supply contracts	Most goods made with 50% as much material, many now used for twice as long	Manufacturing inputs reduced by 50% compensated by new designs and manufacturing practices. No necessary reduction output.	Restoration of reduced material supplies allows expansion in output, although some goods will in future be smaller and used for longer than previously.
Electricity	Wind and solar supplies grow as rapidly as possible, with associated storage and distribution. Rapid expansion in electrificiation of end-uses.	Four-fold increase in renewable generation from 2020, all non-electrical motors and heaters phased out.	All energy supply is now non-emitting electricity.	Demand for non-emitting electricity drives ongoing expansion in supply.
Fossil fuels	Rapid reduction in supply and use of all fossil fuels, except for oil for plastic production	Fossil fuels completed phased out		Development of Carbon Capture and Storage (CCS) may allow resumption of use of gas and coal for electricity

Figure 17. UK FIRES Absolute Zero Roadmap Milestones by Sector
Source: UK FIRES, 2019

In addition to the 2019 UK Absolute Zero Roadmap study, Nelson and Allwood also published a review paper of 12 scenarios from 9 published deep decarbonization studies for the U.K. from 2015 through 2020 (Nelson and Allwood, 2021). The study analyzed the role for innovations in enabling two types of disruptions, or a swift deviation from current trends, which are technological disruptions and behavioral disruptions. Technological disruptions are based on using new methods, systems or devices that are the result of scientific knowledge, whereas behavioral disruptions are demand-side change to personal decisions or activities that affect energy use, consumption and travel (Nelson and Allwood, 2021). Based on their review of 12 scenarios, the study synthesized the maximum quantitative emissions reductions for innovations and their role in behavioral and technological disruptions in Figure 18 shown below.

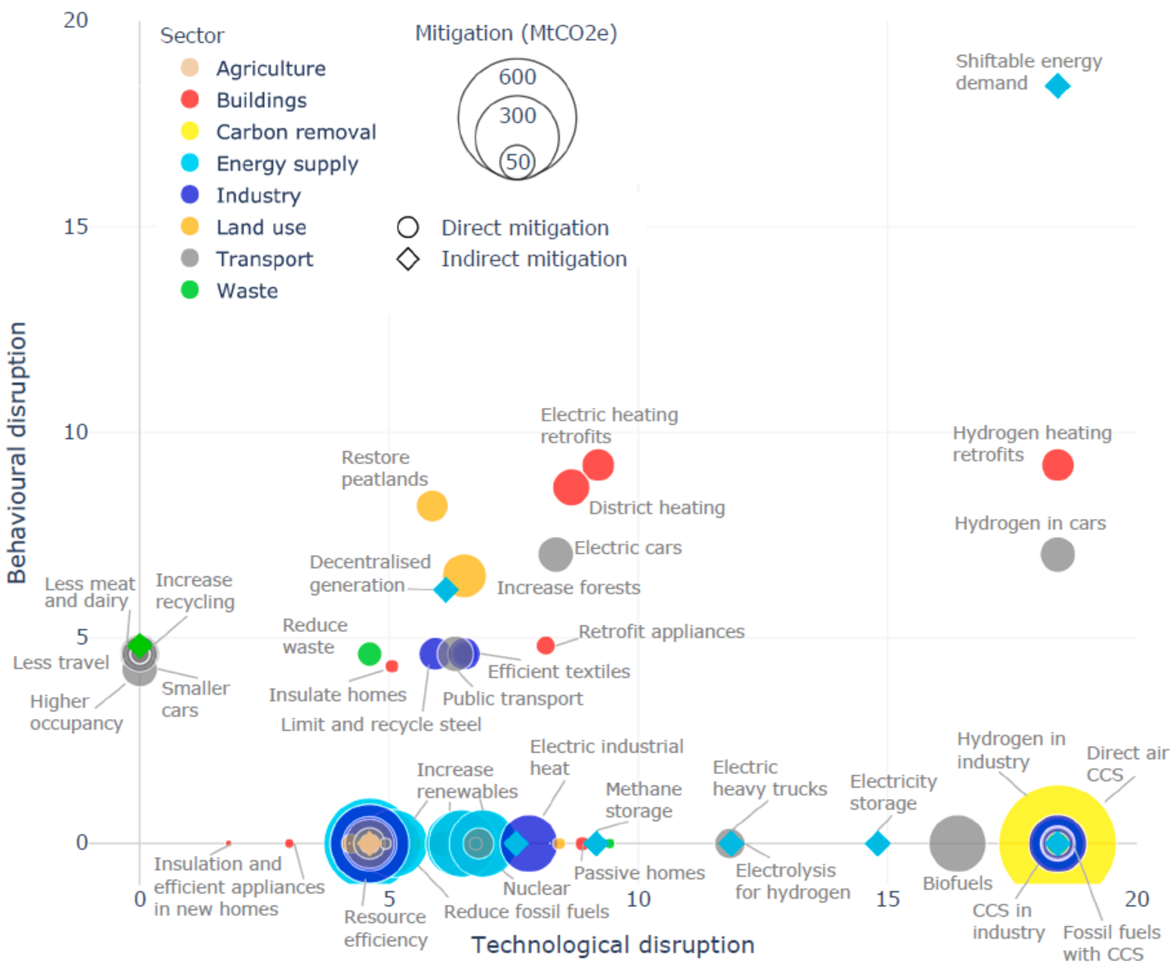


Fig. 2. The maximum disruption and abatement for all mitigation options. The size of the bubble gives the relative mitigation potential.

Figure 18. Disruption and Emissions Abatement Potential for Mitigation Options in U.K. Deep Decarbonization Studies

Source: Nelson and Allwood, 2021.

As seen in the figure above, the review found that transport sector had the most (23) mitigation options of all sectors, followed by 18 options in energy supply and in industry, and 15 in buildings (Nelson and Allwood, 2021). The fewest available mitigation options are in carbon removal, land-use, agriculture and waste. The study also found that purely technological mitigation options are mostly concentrated in energy supply and industrial sectors, and the most technologically disruptive (i.e., greatest change in market share relative to today) cluster is those of unproven technologies such as carbon capture and sequestration and hydrogen. In contrast, there are generally fewer options for behavioral disruption identified from existing studies and are less "disruptive" because behavioral options are often adjustments of existing behavior. Nevertheless, some behavioral options, such as limiting material demand and halving meat consumption, could result in comparable emissions reductions as technological options such as electrifying car fleet or retrofitting home appliances. The study also identified four clusters of both technological and behavioral disruptions: reducing waste, switching travel modes, electrifying and retrofitting homes. These findings suggest that there is a distinct bias for technological disruption in existing studies, with 64% of mitigation options in reviewed scenarios exclusively relying on technology, 20% relying on purely behavioral options, and only 16% relying on both technological and behavioral options (Nelson and Allwood, 2021). The study also found greater bias towards technological options in reports that were published by institutions closest to the government, which highlights political challenges of behavioral interventions in achieving deep decarbonization. However, there are also signs that this bias is beginning to change, as the Climate Change Committee's 2020 policy proposal included a Balanced Net Zero pathway where 16% of emission reductions were attributable to social or behavioral change (Nelson and Allwood, 2021).

3.3 France's Low Carbon Strategy

In addition to the U.K., the Ministry for the Ecological and Solidarity Transition (MEST) for France also released a national low carbon strategy in 2020 that explicitly considers social and technological innovations to change how goods and services are consumed. In its this national strategy document, France explicitly calls for "sobriety" or moderation (*sobriété*) as a third lever to complement decarbonization and energy efficiency for its low carbon transition (France MEST, 2020). By referring to consuming with moderation (i.e., less) goods and services with high environmental impacts, this lever for low carbon transition emphasized significantly changing the way of living and consumption in the medium to long-term as related to travel and goods and services. To promote this new concept of "sobriety," the strategy calls for increasing education, information and awareness of citizens as key to changing individual and collective behavior, along with supply chain regulations and clear price signals. The strategy also calls for developing tools to help assist citizens with their individual low carbon transition by enabling them to calculate their own impacts, receive more information and communication to support a circular way of living.

At a sectoral level, France's Low Carbon Strategy discussed key strategies for achieving sobriety in its low carbon transition and included specific examples of technological and social innovations needed to meet its modeled reduction goal for the sector. It also included some quantitative goals and supporting policies needed to promote the adoption of selected innovations. For a low carbon transition in the transport sector, for instance, the strategy identified 5 key levers to achieve a 28% reduction in transport CO_2 emissions from 2015 levels by 2030, and complete decarbonization by 2050 (France MEST, 2020). Of the 5 key levers, 3 are directly related to the concept of sobriety, including: controlling transport demand growth, mode shifting and optimized vehicle use for both passenger and freight transport. The other two levers focus on improving vehicle energy performance and decarbonizing vehicle energy fuel consumption.

For mode shifting, the strategy included a target of increasing the bike mode share of short-distance trips from 3% to 12% by 2030 and 15% by 2050, and calls for improving network performance to encourage air to rail mode shift, and boosting the competitiveness of rail freight and river transport to promote freight mode shift. For managing increased demand, the strategy calls for more ambitious teleworking objectives, supporting the development of shared work spaces, and providing on-site services for workers. To optimize vehicle use, the strategy supports shared mobility services and car-sharing for short-distances and non-public transit zones by developing supporting tools and infrastructures, and optimizing the weight and volume of freight loads.

Specific policies that were identified as needed to support the transport low carbon transition include price signal incentives and regional urban planning and development policies, and policies to support alternative, active and collective or shared means of passenger transport, and collective and collaborative modes of freight transport. To track future progress, the strategy document also identified specific indicators for the key levers identified, such as shares of non-motorized versus motorized transport for commuting, average occupation rate of cars and filling rate of heavy goods vehicles, and number of remote work days per week and number of remote workers (France MEST, 2020).

3.4 Germany's Climate Action Plan 2050

In 2016, Germany's Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BUMB) issued the national Climate Action Plan 2050 that reaffirms the country's 2050 GHG emission reduction goal of 80-95% and guiding principle of becoming largely greenhouse gas neutral by 2050. It is also intended to serve as a guiding framework for sectoral developments through 2030 in order to meet the interim target of 55% reduction from 1990 levels by 2030, with emission reduction milestones and necessary measures identified for each sector. Depending on the sector, the measures identified in the Climate Action Plan 2050 included many technological and social innovations for reducing energy demand and emissions.

In the transport sector, for example, there is emphasis on shared mobility systems and digitalization, including through: smart public transport networks and new shared mobility services, automated and networked mobility that optimizes traffic flows, avoid congestion, reduce traffic volume for finding parking, and modern digital technologies to help enhance public transport attractiveness (BUMB, 2016). Other measures included more social innovations, such as carefully planned integrated urban development and attractive streets, needs-oriented modeling of street environment and urban development based on compact city model, modern ways of working to reduce rush hour traffic, and increasing the use of cargo biking for express parcel courier and small-scale transport services.

3.5 Policy Implications and Case Study of Policies for Supporting Innovation in EU Energy and Climate Plans

As evidenced in the growing focus on moderating and reducing consumption, which helps reduce related energy demand and GHG emissions, in national low carbon strategies and reports for European countries, there is also an emerging field of research focused on the concept of sufficiency within the last five years. Although the specific definitions and scope varies in studies, sufficiency can generally be described as "as "strategy of achieving absolute reductions of the amount of energy-based services consumed, notably through promoting intrinsically low-energy activities, to reach a level of enoughness that ensures sustainability" (Zell Ziegler et al., 2021). Energy sufficiency is increasingly becoming recognized as one of the three strategies needed for energy sustainability and achieving carbon neutrality, in addition to energy efficiency and renewable energy. To assess how sufficiency is being considered in existing European national policies and plans, Zell Ziegler et al. 2021 systematically reviewed existing 27 national energy climate plans and 15 long-term strategy documents for European countries analyzed 230 sufficiency-related policy measures.

To be more specific, Zell Ziegler et al. 2021 classified measures that can help achieve sufficiency into three broad categories of:

1. Reduction measures that reduces energy services by reducing utility units of energy services, such as passenger-kilometer travelled or square meter of building space heated
2. Substitution measures that changes the quality aspects of energy services by replacing them with alternative services that require little or zero energy consumption and implies changes in social and behavioral practices
3. General measures that alter the regulatory or incentive framework to reduce GHG emissions

Based on this categorization, Zell Ziegler et al. 2021's review found a disproportionate focus on transport measures, weighted by many substation measures that focused primarily on mode shifting from road transport to slow (non-motorized) or public transit modes and electrification or biofuel adoption for vehicles (see Figure 19). In contrast, very few measures included in existing national plans were directly aimed at reducing energy services. Most of the transport measures included in the reviewed policy documents were fiscal and economic instruments, including many focused on infrastructure development to support greater use of rail and bicycling.

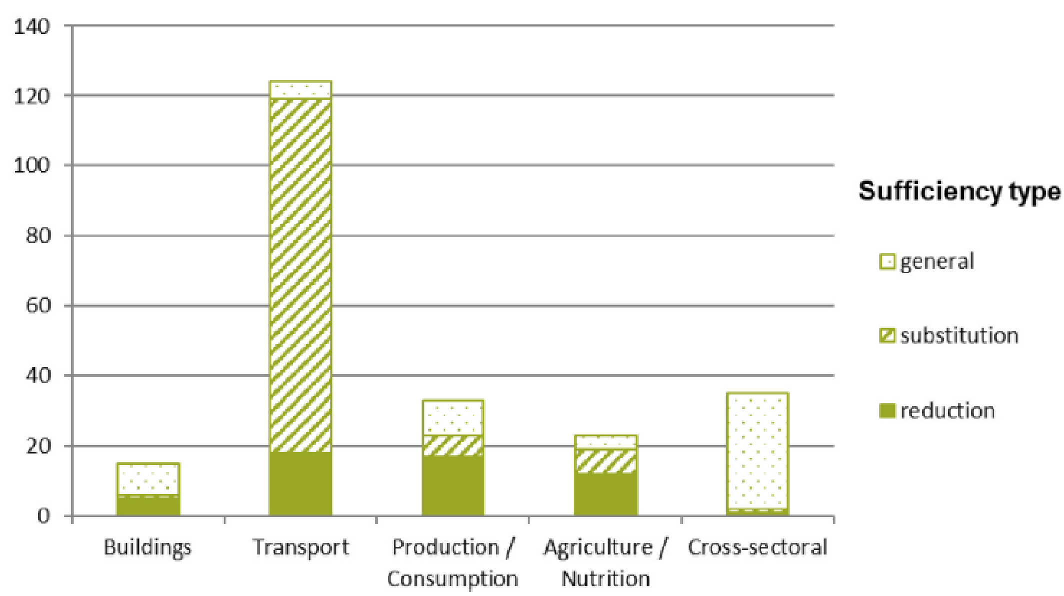


Figure 19. Number of Sufficiency Measures by Sector and Type from Zell Ziegler et al. 2021 Review of European National Policy Documents

Source: Zell Ziegler et al. 2021

The review also found limited representation of sufficiency measures for the buildings sector, with only a few instances of sufficiency measures such as limiting increased living spaces, changing thermal comfort norms and controlling growth in appliance or electronic gadget ownership included. In terms of policy instrument type, most of the measures were information-based awareness campaigns, which could be the result of buildings being private, rather than public, sector driven.

From a geographical perspective, Austria, France and Germany stood out as leaders in including sufficiency measures in their national plans and strategies, with most other countries having included 5 to 10 sufficiency-related measures in their policy documents (see Figure 20). France included specific sufficiency assumptions and trends in modeling its long-term strategy scenario, including residential sector behavior changes, moderation in mobility demand growth, and moderate reductions in meat consumption (Zell Ziegler et al. 2021). In practice, however, the review found that development and implementation of concrete measures have been more difficult. For example, some of the proposed sufficiency policy measures from the French Citizen's Convention have been scaled back for implementation. Instead of the proposed 4 hours train travel duration criteria for banning short-distance flights, the criterion was lowered to only 2.5 hours, which directly reduces the share of domestic flights impacted. Similarly, in Austria, sufficiency has been included in academic and government discourse and some government programs and recognized as a strategy element in 2019 under a new government, but is still not part of public discourse yet. Austria's long-term strategy included ambitious measures such as more durable products, fewer flights, higher car occupancy, less meat consumption, community buildings but there have been no specific follow-up policies or measures yet for implementation. Another key policy challenge identified from the review is that governments generally see a limited role for regulatory instruments in supporting sufficiency measures.

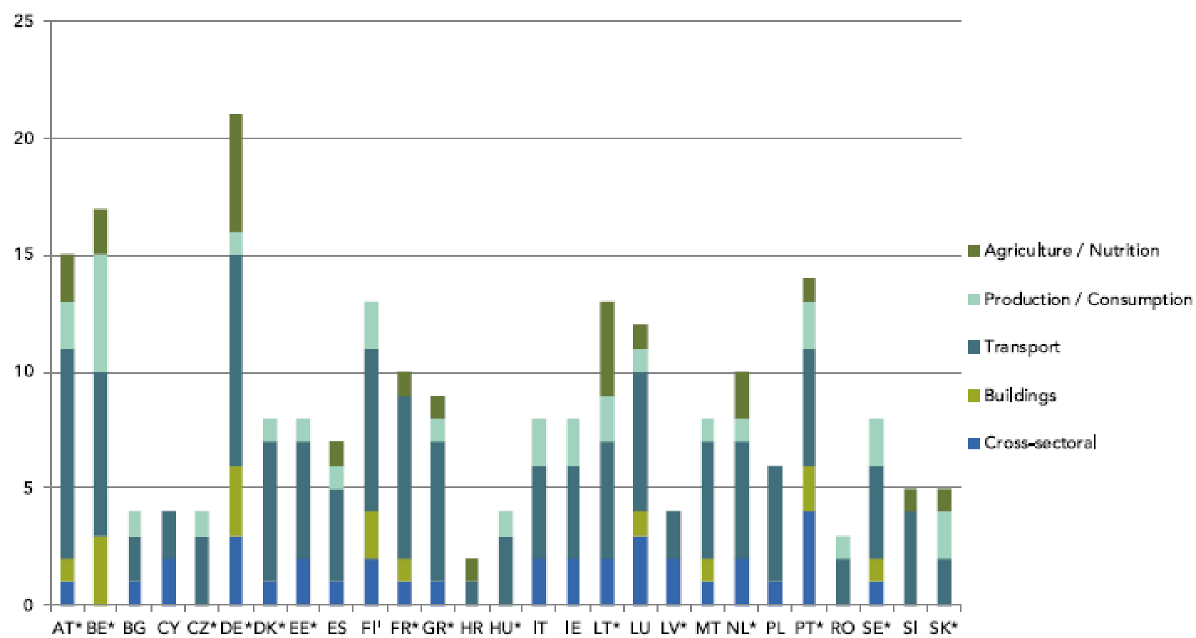


Figure 20. Geographical Distribution of Sufficiency Measures from Zell Ziegler et al. 2021 Review of European National Policy Documents

Source: Zell Ziegler et al. 2021

4. References

Building References

Betram, N., Fuchs S., Mischke, J. et al. 2019. “Modular construction: From projects to products.” McKinsey & Company report. https://www.mckinsey.com/business-functions/operations/our-insights/modular-construction-from-projects-to-products

Gerber, D. L., Vossos, V., Feng, W., Marnay, C., Nordman, B., & Brown, R. (2018). A simulation-based efficiency comparison of AC and DC power distribution networks in commercial buildings. *Applied Energy*, *210*(December), 1167–1187. https://doi.org/10.1016/j.apenergy.2017.05.179

IEA (2019), *Case Study: Artificial Intelligence for Building Energy Management Systems*, IEA, Paris https://www.iea.org/articles/case-study-artificial-intelligence-for-building-energy-management-systems

National Renewable Energy Laboratory. 2020. “Assessing and Reducing Plug and Process Loads in Retail Buildings.” https://www.nrel.gov/docs/fy20osti/76998.pdf

Passive House Alliance. 2022. “Passive House FAQs.” https://www.phius.org/what-is-passive-building/passive-house-faqs

Petersen A., Gartman M., and J. Corvidae. 2019. “The Economics of Zero-Energy Homes: Single-family Insights.” Rocky Mountain Institute Study. https://rmi.org/insight/economics-of-zero-energy-homes/

Sheppy, M.; Lobato, C.; Pless, S.; Gentile Polese, L.; and Torcellini, P; "Assessing and Reducing Plug and Process Loads in Office Buildings." National Renewable Energy Laboratory, Tech. Rep. NREL/FS-5500-54175, 2013.

Tracy, P. 2016. “How IOT is lowering the cost of building management systems.” Enterprise IOT Insights. August 8, 2016. https://enterpriseiotinsights.com/20160808/buildings/building-management-system-tag31-tag99

U.S. Department of Energy. 2022. “Better Buildings Solution Center: Plug & Process Loads.” https://betterbuildingssolutioncenter.energy.gov/alliance/technology-solution/plug-process-loads

U.S. General Services Administration. 2022. “Sustainable Facilities Tool: Plug Loads.” https://sftool.gov/learn/about/426/plug-loads

Industry References

BBC, 2020. " Tesco to ditch plastic-wrap for multipack tins", January 24. https://www.bbc.com/news/business-51223214

Blueland, 2022. "How it works". https://www.blueland.com/how-it-works [accessed on January 24, 2022]

Cherry, Catherine, Kate Scott, John Barrett, and Nick Pidgeon. 2018. “Public Acceptance of Resource-Efficiency Strategies to Mitigate Climate Change.” *Nature Climate Change* 8 (11): 1007–12. https://doi.org/10.1038/s41558-018-0298-3.

Cornall, J. 2020. “Magnum launches tubs made with recycled plastic”, August 13. https://www.dairyreporter.com/Article/2020/08/13/Magnum-launches-tubs-made-with-recycled-plastic

Fetner, Hannah, and Shelie A. Miller. 2021. “Environmental Payback Periods of Reusable Alternatives to Single-Use Plastic Kitchenware Products.” *International Journal of Life Cycle Assess*ment 26 (8). https://doi.org/10.1007/s11367-021-01946-6.

Hahladakis, John N., and Eleni Iacovidou. 2018. “Closing the Loop on Plastic Packaging Materials: What Is Quality and How Does It Affect Their Circularity?” *Science of the Total Environment* 630. https://doi.org/10.1016/j.scitotenv.2018.02.330 .

Hoornweg, Daniel, and Perinaz Bhada-Tata. 2012. “What a Waste: A Global Review of Solid Waste Management.” World Bank. https://doi.org/10.1201/9781315593173-4 .

Ivanova, Diana, John Barrett, Dominik Wiedenhofer, Biljana Macura, Max Callaghan, and Felix Creutzig. 2020. “Quantifying the Potential for Climate Change Mitigation of Consumption Options.” *Environmental Research Letters* 15 (9). https://doi.org/10.1088/1748-9326/ab8589 .

Jambeck, Jenna R., Roland Geyer, Chris Wilcox, Theodore R. Siegler, Miriam Perryman, Anthony Andrady, Ramani Narayan, and Kara Lavender Law. 2015. “Plastic Waste Inputs from Land into the Ocean.” *Science* 347 (6223). https://doi.org/10.1126/science.1260352 .

Kaza, Silpa, and Lisa Yao. 2018. “What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050.” World Bank. https://doi.org/10.1596/978-1-4648-1329-0_ch2 .

Law, Kara Lavender, Natalie Starr, Theodore R. Siegler, Jenna R. Jambeck, Nicholas J. Mallos, and George H. Leonard. 2020. “The United States’ Contribution of Plastic Waste to Land and Ocean.” Science Advances 6 (44): 1–8.

https://doi.org/10.1126/sciadv.abd0288 .

Loop, 2022. "How it works". https://loopstore.com/how-it-works [accessed on January 24, 2022]

Material Economics. 2018. “Sustainable Packaging: The Role of Materials Substitution.” PackREPORT. Vol. 53. https://doi.org/10.51202/0342-3743-2021-5-007 .

Material Economics. 2019. “Industrial Trans- Formation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry.”

Mohan, A. M. 2021. " Magnum Tub is First to Use Certified Circular Plastic“, January 14. https://www.packworld.com/issues/sustainability/article/21221095/magnum-tub-is-first-to-use-certified-circular-plastic

Notpla, 2022. "Products". https://www.notpla.com/products-2/ [accessed on January 24, 2022]
PlasticsEurope. 2018. “The Facts 2018.” PlasticsEurope.

The Ellen MacArthur Foundation. 2020. “Upstream Innovation: A Guide to Packaging Solutions.” https://emf.thirdlight.com/link/xgfhlc17d1oc-qtv2v7/@/#id=2 .

Waitrose, 2019. " Waitrose makes canny move with removal of plastic on bestselling staple foods", October 1. https://waitrose.pressarea.com/pressrelease/details/78/NEWS_13/11678

Walmart, 2019. " Update: Walmart Canada prevents 1.1 million pounds of plastic from entering its supply chain", October 24. https://www.walmartcanada.ca/news/2019/10/24/update-walmart-canada-prevents-11-million-pounds-of-plastic-from-entering-its-supply-chain

Transport References

Allen J., Piecyk M., Cherrett T. et al. 2021. Understanding the transport and CO2 impacts of on-demand meal deliveries: A London case study. *Cities* 108: 102973.

Dillman K., Czepkiewicz M., Heinonen J. et al. 2021. Decarbonization scenarios for Reykjavik’s passenger transport: The combined effects of behavioural changes and technological developments. *Sustainable Cities and Society* 65: 102614.

Dubois G., Sovacool B., Aall C., et al. 2019. It starts at home? Climate policies targeting household consumption and behavioral decisions are key to low-carbon futures. *Energy Research & Social Science* 52: 144-158.

Ivanova D., Barrett J., Wiedenhofer D. et al. 2020. Quantifying the potential for climate change mitigation of consumption options. *Environmental Research Letters* 15: 093001.

Jochem P., Frankenhauser D., Ewald L. et al. 2020. Does free-floating carsharing reduce private vehicle ownership? The case of SHARE NOW in European cities. *Transportation Research Part A* 141: 373-395.

Khanna N., Zhang J., Lu H., et al. 2021. *Energy Demand Changes Induced by Technological and Social Innovations: A Review of Sectoral and Global Perspectives*. LBNL report.

Sengul B. and H. Mastofi. 2021. Impacts of E-Micromobility on the Sustainability of Urban Transportation – A Systematic Review. *Applied Sciences* 11: 5851.

Sun B., Garikaptai V., Wilson A., and A. Duvall. 2021. Estimating energy bounds for adoption of shared micromobility. *Transportation Research Part D* 100: 103012.

Wilson C., Kerr L., Sprei F., et al. 2020. Potential Climate Benefits of Digital Consumer Innovations. *Annual Review of Environment and Resources* 45: 113-44.

Cross-sector References

BP. *2019 Statistical Review of World Energy.* https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf

Calma, J. 2021. *Google launches new features to help users shrink their carbon footprints.* The Verge. October 6, 2021. https://www.theverge.com/2021/10/6/22711623/google-climate-change-greenhouse-gas-emissions-carbon-footprint-maps-search-travel

Center for Sustainable Systems, University of Michigan. (2021). *U.S. Food System Factsheet*. Pub. No. CSS01-06. https://css.umich.edu/factsheets/us-food-system-factsheet

Citicap Project Team, Urban Innovative Actions. (2021). *City of Lahti Launches a Personal Carbon Trading Scheme for Citizens.* https://www.uia-initiative.eu/en/news/city-lahti-launches-personal-carbon-trading-scheme-citizens

Dong, L. (2021, December 22). *How can individuals benefit from carbon inclusion? Shenzhen "creates" a low-carbon planet.* Sohu. https://www.sohu.com/a/510666002_115479

Dresner, S. (2005). *Distributional, Practical and Political Implications of Carbon Taxing and Trading, paper delivered at workshop run by UK Energy Research Centre*. www.ukerc.ac.uk/content/view/110/57

Fan, J., Wang, S., Wu, Y., Li, J., Zhao, D. (15 January, 2015). *ENERGY-USE CHOICES AND ALLOWANCE TRADING UNDER THE PERSONAL CARBON TRADING SCHEME*. Nature Resource Modeling, 28(1), 1-17. https://onlinelibrary.wiley.com/doi/abs/10.1111/nrm.12054

Fan, J., Li, J., Wu, Y., Wang, S., Zhao, D. (2016, March 7). *The effects of allowance price on energy demand under a personal carbon trading scheme.* Applied Energy, 170, 242-249. https://www.sciencedirect.com/science/article/pii/S0306261916302677?casa_token=G1plHH8yE1IAAAAA:3l1WtNd3z_kLOTBons-DgVwk4nIwCq8gjPyrPO6zOQbZ0kYifbcgHgn_DBvNCQkfXUCJZZz6zA#s0015

Lane, C., Harris, B., & Roberts, S. (2008). *An analysis of the technical feasibility and potential cost of a personal carbon trading scheme: A report to the Department for Environment, Food and Rural Affairs.* Accenture, with the Centre for Sustainable Energy (CSE). https://www.cse.org.uk/downloads/reports-and-publications/policy/technical-feasibility-personal-carbon-trading.pdf

Nerini, F.F., Fawcett, T., Parag, Y., Ekins, P. (2021, August 16). *Personal carbon allowances revisited*. Nature Sustainability, 4, 1025–1031. https://www.nature.com/articles/s41893-021-00756-w

Starkey, R. (2011, November 28). *Personal carbon trading: A critical survey Part 2: Efficiency and effectiveness.* Ecological Economics, 73, 19-28. https://www.sciencedirect.com/science/article/pii/S0921800911003946?casa_token=bDscWXmUVC8AAAAA:kS8kYayYUISpevJXltT8gvS4GA_xGHdw6GdOGQHXrVNcXPlB0njXlqpP7LYfJn3Tg-rX-jaBUA

World Bank. (2019, September 23). *How Much Do Our Wardrobes Cost to the Environment?* https://www.worldbank.org/en/news/feature/2019/09/23/costo-moda-medio-ambiente

(2019) *Energy use per person*. BP Statistical Review of World Energy https://ourworldindata.org/grapher/per-capita-energy-use

United Nations Framework Convention on Climate Change (UNFCCC) 2022. *Alipay Ant Forest: Using Digital Technologies to Scale up Climate Action.* https://unfccc.int/climate-action/momentum-for-change/planetary-health/alipay-ant-forest

Zhang, Y., Chen, J., Han, Y., et al. (2021, February 2). *The contribution of Fintech to sustainable development in the digital age: Ant forest and land restoration in China.* Land Use Policy, 103, 105306. https://www.sciencedirect.com/science/article/pii/S0264837721000296?casa_token=2AsfLE3ZwfYAAAAA:Kht2wd0_xVYGbTNg9OjgV9ha-Cwr3NrKL5MdkARe8P_q_XPO-5u_LZXwePbSGPMThXpxRMZ-3cw

Carbon Neutrality Roadmaps References

Allwood, J.M., Dunant C.F., Lupton R.C. et al. 2019. *Absolute Zero: Delivering the UK's climate change commitment with incremental changes to today's technologies*. Cambridge: University of Cambridge.

Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BUMB). 2016. *Climate Action Plan 2050*. Berlin: Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety.

International Energy Agency (IEA). 2021*. Net Zero by 2050: A Roadmap for the Global Energy Sector*. Paris: IEA.

IEA. 2021. *An Energy Sector Roadmap for Carbon Neutrality in China*. Paris: IEA.

Ministry for the Ecological and Solidarity Transition (MEST) of France. 2020. *National Low Carbon Strategy*. Paris: Ministry for the Ecological and Solidarity Transition of France

Nelson S. and J.M. Allwood. 2021. Technology or behavior? Balanced disruption in the race to net zero emissions. *Energy Research & Social Science* 78: 102124.

Zell-Ziegler C., Thema J., Best B. et al. 2021. Enough? The role of sufficiency in European energy and climate plans. *Energy Policy* 157: 112483.

2021年度 日本の民生部門等における
エネルギー需要変化の研究とりまとめ　報告書

大阪大学 大学院工学研究科 環境エネルギー工学専攻
下田研究室

１．まえがき

2021 年に閣議決定された地球温暖化対策計画 [1)]は 2030 年度の温室効果ガス排出削減目標を 2013 年度比 46%とし，2050 年までにカーボンニュートラルを実現するとしている．本研究が対象とする民生部門は特に高い 2030 年度二酸化炭素（CO_2）排出削減目標が設定されている．2013 年度 208 $MtCO_2$であった家庭部門は 66%，238 $MtCO_2$であった業務その他部門は 51%であり，削減目標を実現するための方策を検討することは喫緊の課題である．また，地球温暖化対策計画では民生部門削減目標の根拠資料として具体的な対策技術の普及目標とそれによりもたらされる削減量が示されている．この削減量推計では対策導入によりもたらされる削減量を削減原単位（1 単位の対策導入によりもたらされる削減量）と対策導入量の積和により定量化しており，松岡ら [2)]，Taniguchi-Matsuoka ら [3)]が示しているように，エネルギー需要を形成する重要因子（生活行動など)，需要家の多様性などが無視されていることから，期待される削減量に大きな推計誤差が含まれる可能性がある．民生部門に関する対策導入効果推計の精度を高めるための一つの方向性は，エネルギー需要が決定される構造と，住宅・建築物の多様性を考慮したうえでその将来変化を明らかにし，将来もたらされうる CO_2 排出削減量を定量化することである．近年では，これを実現するためのシミュレーション技術（Building Stock Energy Modeling など）が開発されている．我が国の家庭部門では，松岡ら [2)]，Taniguchi-Matsuoka ら [3)]，杉山ら [4)]，Shimoda ら [5)]の一連の研究がある．これらの推計では，推計単位を世帯とし，世帯員の生活行動に基づいて機器の稼働状況を決定するなど，エネルギー需要が決定される構造を推計モデル上で再現し，加えて，世帯の属性やそれによって特徴づけられる需要決定要因の多様性を考慮しており，削減見込みの推計精度が高い．また，季節別・時刻別のエネルギー需要の予測が可能である．Yamaguchi ら [6)]は我が国の業務部門（事務所，宿泊，医療，小売，学校の 5 用途のみ）を対象としてエネルギー需要を推計するモデルを開発した．この推計では上記家庭部門と同様の方法を採用し，業務施設を単位としてエネルギー需要が決定される構造を再現したうえで，用途・業態，立地，施設規模，設備構

成等に関する多様性を考慮して[7]，エネルギー需要，CO_2排出量，季節別・時刻別エネルギー需要の推計を行う．一方で，これらの推計は部門別に行われてきたものであり，民生部門全体のエネルギー需要の推計は行われていない．

海外では同様のアプローチにより，Sandberg ら[8]はノルウェーの民生部門を対象として Zero emission 住宅・建築物（ZEB）の普及によるエネルギー需要の変化を推計した．Langevin ら[9]は米国の建築部門におけるエネルギー需要を推計するモデルを確立し，大幅な CO_2 排出削減が可能であることを示した．Hirovonen ら[10]はフィンランドの民生部門を対象として建築物の改修による CO_2 排出削減ポテンシャル，電力需要の変化を推計した．この推計では，建築物エネルギー性能の向上，暖房・給湯熱源の電化により電力需要の季節・時刻特性が大きく変化することが示されている．

前述の我が国家庭部門・業務部門，EU，米国を対象とする検討では，国家スケールでエネルギー需要の変化が推計されている．このような検討により推計されるエネルギー需要データは，エネルギー供給側の検討にも有用である．一方で，エネルギー供給側の検討に使用可能な，将来のエネルギー需要データは十分に開発されていない．Boßmann ら[11]は技術普及シナリオの下で民生部門の省エネルギー，熱供給における電化，電気自動車の普及による電力需要の変化を考慮し，ドイツ，イギリスの電力需要負荷持続曲線の変化として定量化した．このようなデータは電力需給運用に関する検討に応用可能である．Grubler ら[12]は世界の全エネルギー需要部門を対象としてエネルギー需要の大幅削減を考慮した Low Energy Demand（LED）シナリオを提案し，エネルギー供給システムを含むエネルギーモデルにより LED シナリオの実現により地球温暖化による温度上昇を 1.5℃に抑えることが可能であることを示している．このようにエネルギーの需要側，供給側を統合化した分析は有用である．

以上の背景から，本研究は住宅・業務施設ストックを対象として各種技術の普及シナリオの下で時刻別電力需要を含むエネルギー需要，部門全体の CO_2 排出量の変化を推計する．シナリオは 2030 年度までは地球温暖化対策計画に基づくものとし，2030 年以降は脱炭素化のための追加的な技術普及，熱用途の電化を考慮する．

２．エネルギー需要の推計方法

２．１　家庭部門のエネルギー需要の推計方法

昨年度の報告書においてモデルの詳細を説明しているため、概要のみを述べる。家庭部門のエネルギー需要推計には既報[2)～5)]のモデル，Total Residential End-use Energy Simulation（TREES）モデルを用いた．本モデルでは，まず代表世帯として各都道府県の世帯の 0.03％をランダムに抽出する．次に，それらの世帯毎に居住都道府県，世帯属性情報（世帯の人数，構成，年収，世帯員の年齢，性別，就業形態など）や住宅情報（延床面積，建て方，建築年，所有関係など）を国勢調査及び住宅土地統計調査から確率的に決定する．続いて，代表世帯が居住する住宅の熱性能，機器の台数・性能，給湯・暖房機器の種類を決定する．住宅の熱性能は建築年毎の熱性能区分（無

断熱，1980 年基準，1992 年基準及び 1999 年基準）の比率から決定する．テレビ，冷蔵庫，エアコンの台数，サイズ，製造年は，世帯の人数，年収，年齢，住宅の延床面積，建築年等を説明変数とする回帰モデルにより決定し，省エネ性能カタログ，メーカー仕様書に基づいて仕様を決定する．給湯・暖房機器の種類は世帯の人数，年収，住宅の建て方，所有関係，建築年，都市ガス供給の有無，電力会社区分などに基づいて決定する．

次に，これらの条件の下で代表世帯のエネルギー需要を 5 分タイムステップで推計する．まず，時間の使い方に関する社会調査である社会生活基本調査に基づいて算出された時間の使い方に関するデータベースに基づいて計算対象期間における生活行為を確率生成する．行為の種類と行為実施場所に対応して定義された機器操作確率に基づき機器の稼働スケジュールを確率的に決定する．以上のように決定した機器の稼働スケジュール及び機器の稼動時消費電力に基づいて機器のエネルギー消費量を決定する．照明と暖冷房については居住者の在室状況と自然照度・温度を考慮して稼働を決定する．暖冷房については熱回路網法を用いた動的熱負荷計算によって暖冷房熱負荷を計算する．この計算を行うために住宅の間取りや壁・窓の仕様を定めており，集合・戸建それぞれについて延床面積・間取り等が異なる 6 つの住宅モデルを考慮し，前述の断熱性能 4 水準と合わせて 48 の住宅モデルを用いている．計算では気象データ，設定温度，人体・機器内部発熱を考慮し，暖冷房の稼働の決定，熱負荷の算出を経て，各部屋で使用されている機器のエネルギー消費を定量化する．給湯については，行動スケジュール，行為別給湯使用量，設定温度，日別外気温の関数で表された上水温度に基づいて給湯熱需要を算出し，各給湯器のエネルギー効率及び運転仕様に基づいて，給湯エネルギー消費量を決定する．

２．２　業務部門のエネルギー需要の推計方法

業務部門は Yamaguchi ら [6)] のモデルを用いた．本モデルも家庭部門の TREES と同様に業務施設ストックデータに基づいて業務施設を代表する代表モデルをサンプリングし，代表モデルを用いたエネルギー需要シミュレーションを行う．シミュレーションでは米国エネルギー庁が開発している EnergyPlus8.6 [13)] を用い，シミュレーション結果を代表モデルの延床面積により除して延床面積当たりエネルギー消費原単位を定量化し，代表モデルが代表する延床面積との積和によりエネルギー消費量の総量を定量化する．対象は事務所，宿泊，医療，小売，学校（小中高校）であり，2013 年度の延床面積は 1,255 百万㎡である．当該ストックは業務その他部門の CO_2 排出量 238 $MtCO_2$ のうち 60%，142 $MtCO_2$ をカバーしている．

図 1 にモデル開発手順を示す。図の手順では、手順 2 における代表モデルの設計、手順 3 におけるシミュレーションによって業務施設でエネルギー需要が決定される構造を反映したうえで、手順 1 の類型化および手順 4 の積み上げによって対象とする建築ストック全体でのエネルギー需要の定量化が可能となる。そのため、ある程度現実的な機器・設備の運用条件を想定することによって、導入技術の相互作用を含めて、将来における技術的な変化がもたらしうるエネルギー需要の変化を定量化することが可能である。手順 1 では業務施設の立地、用途、規模、空気調和設備種別にストックを類型化した。図中手順 3 では業務施設 1 棟単位で算出したエネルギー需要を

延床面積あたりで原単位化し、手順 4 において類型別延床面積と積和することで対象地域全体のエネルギー需要を推計した。以下では各手順の詳細を述べる.

1. ストックの類型化

エネルギー需要に大きな影響をもつ属性に基づいてストックを類型化する。

↓

2. 代表モデルの設計

各類型を代表する業務施設モデル（代表モデル）を設計する。

↓

3. ストック類型別エネルギー需要原単位の推計

代表モデルに対応する入力条件を用いてシミュレーションを行い、エネルギー需要を推計する。ここで得られたエネルギー需要を原単位化し、代表モデルに対応するストック類型のエネルギー需要原単位とする。

↓

4. エネルギー需要の積み上げ

各類型のエネルギー需要原単位とストック数の積をとり、各類型に含まれるストックのエネルギー需要を定量化する。得られたエネルギー需要をすべての類型について合計し、対象とするストック全体のエネルギー需要として定量化する。

図 1　エネルギー需要モデル開発手順

２．２．１　ストックの類型化とストック構成の定量化

Yamaguchi ら[6]のモデルでは延床面積を 2013 年度のデータで固定していたが，今年度，経年変化を考慮できるものとし，各年の推計を可能とした．本モデルでは施設用途別の延床面積を所与のものとして与え，その内訳を定量化する．小売以外の施設用途別延床面積はエネルギー・経済統計要覧（EDMC）[14]に掲載されている用途別延床面積を用いた．小売施設は，商業小売店舗の売場面積に関するセンサスデータである商業統計[15]に掲載されている業態別の売場面積のデータを用いた．2030 年度は 2015 年に発表された長期エネルギー需給見通し[16]に記載されている業務床面積総量（1,971 百万㎡）を前提とし，小売，学校以外について GDP と施設用途別延床面積の回帰モデルにより 2030 年度の床面積を決定した.2050 年度は 2030 年度に等しいと想定した.次に，業務施設用途別に，立地区分，規模・業態，竣工年別の比率を算出し，各区分の床面積に延床面積を分解した．竣工年代別の比率は建築着工統計[17]に基づく着工床面積，ワイブル分布に基づく減失モデルによりストック更新を模擬して決定した[18]．地域，規模・業態別の比率は秋沢ら[7]による方法を用い，事務所，宿泊施設，商業施設は法人土地・建物基本調査[19]，医療施設，学校は GIS 建物データ[20]から定量化した．立地区分は北海道，東北，関東，北陸，中部，近畿，中国，四国，九州，沖縄の 10 区分とし、代表都道府県の気象データを共通して用いた.

次に，技術項目別に採用技術の水準を決定し，竣工年代別に水準別比率を定め，比率をストッ

クデータに適用することで技術項目別の床面積を定量化した．空調設備，給湯設備の設備種別について熱源の燃料種別，中央・個別の別，空調についてはさらに熱源機器種別，空調システム種別，省エネルギー手法採用区分を考慮した．その他，照明は蛍光灯・白熱灯などの既存照明技術と LED 照明の 2 水準を考慮した.なお,各設備区分項目の比率は互いに独立であることを想定し，その組み合わせの比率を算出した．以上により施設用途，立地区分，規模・業態，設備種別のストック構成比率が定量化される.

（１）施設用途別，規模・業態別，竣工年別床面積定量化

エネルギー経済研究所が発行しているエネルギー・経済統計要覧（EDMC）[14]では業務施設用途別の延床面積の経年変化が掲載されている.地球温暖化対策計画の進捗評価においても EDMC の床面積データが用いられていることから，小売以外の施設用途別延床面積は EDMC に掲載されている用途別延床面積を用いた．小売施設は，商業小売店舗の売場面積に関するセンサスデータである商業統計[15]に掲載されている 2013 年業態別の売場面積のデータを用いた.小売店舗の総床面積に経年変化はなく 2019 年まで一定であると想定した.

次に，延床面積総量を竣工年により分類した．ここではまず，1988 年から 2020 年における業務施設着工床面積に基づいて推計される竣工年別延床面積を定量化し，竣工年別の解体量を模擬するワイブル関数により竣工からの経過年ごとの残存率を与え，竣工年別の残存延床面積の合計から竣工年別ストック構成比率を定量化した．着工床面積は建築着工統計[17]より与えた．本研究では建築着工統計より事務所，店舗，宿泊業，医療業の床面積を利用し，それぞれ事務所，商業施設，宿泊施設，医療施設に対応させた．学校は一律に 50 年で減失すると想定した．なお，1950 年以前の建築物については建築着工統計のデータが存在しない.そこで 1941 年以降の建築物のみ残存するとして，2013 年の法人・土地建物調査[19]における 1950 年以前の竣工年代別割合を利用して，2013 年における竣工年が 1946 年の建築物面積と減失推計モデルによる残存率から 1946 年の着工床面積を推計し，1941 年～1950 年は全て同じ着工量であるとして 1941 年～1950 年の着工床面積を決定した.

次に説明するように、減失推計モデルでは建築構造別のモデルを利用する。そのため、着工床面積を構造別に分解した。建築着工統計では，1951 年～2020 年の構造別延床面積，1988 年～2020 年の用途・構造別延床面積が利用可能である．そこで全国の 1951 年～1987 年のデータに 1988 年～1990 年データの比率を適用し，用途・構造別延床面積を定量化した.

減失推計モデルは小見ら[21]による減失推計モデルを利用した．小見らは建物の経年変化による減失がワイブル分布に従うとし，独自に行ったアンケート調査により分布のパラメータを決定している．調査は 1987 年，1997 年，2005 年の 3 回行われており，1996 年以前は 1987 年の，1997 年から 2004 年は 1997 年の，2005 年以降は 2005 年のワイブル係数を用いた．ただし，このモデルでは 50％の残存率となるまでの経過年数(平均寿命に相当)をパラメータとして用いているが，小見らのワイブル係数を用いた場合，EDMC の総床面積と大きな誤差が生じたため，EDMC と整合するように平均寿命を 15 年延ばして利用した.本研究で利用した建築物竣工後残存率の経年変化を

図 2 に示す．なお，小見らのモデルは非住宅建築物については事務所 RC 造，鉄骨造のみを対象としていることから，建築着工統計で扱っている 6 種類の構造別に法定耐用年数[22]を参照し，各構造を RC 造，鉄骨造のうち耐用年数が近いものにまとめ，RC 造，SRC 造，コンクリート造は小見らの RC 造のパラメータ，鉄骨造と木造は鉄骨造のパラメータを用いた．着工統計の「その他」区分については，鉄骨造，RC 造の元々の比率で按分した．

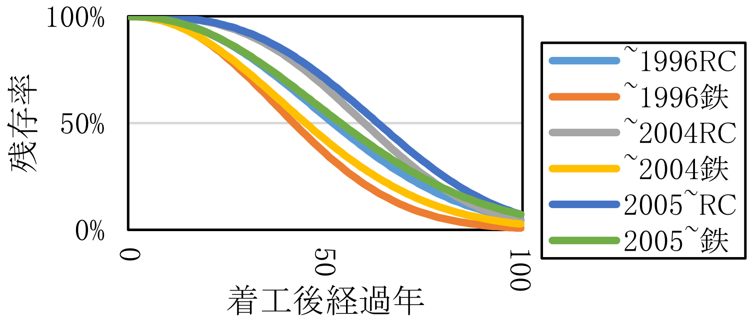


図 2　利用したワイブル分布

これまでに施設用途別，竣工年代別延床面積が定量化される．次に，事務所，宿泊施設，商業施設は法人土地・建物基本調査[19]，医療施設，学校は GIS 建物データ[20]を用い，地域，規模・業態別の比率を推計した．立地区分は北海道，東北，関東，北陸，中部，近畿，中国，四国，九州，沖縄の 10 区分とした．秋沢ら[7]に詳しい．

（2）対策の普及に関する想定

ここでは業務施設ストックにおいて採用されている技術の想定を説明する．考慮した対策のうち，高効率照明の導入は既存照明技術から LED 照明への代替，トップランナー制度による機器の省エネ性能向上についてはコンセント機器のエネルギー性能の向上，新築建築物における省エネルギー基準適合の推進は，竣工時における断熱の採用，省エネルギー基準を満足する空調関連設備の採用を考慮した．ここでは，各対策に対応する技術について①採用技術の水準の決定，②新築・改修実施時の水準別採用比率の決定，③新築・改修床面積との積による設備水準別延床面積の定量化を行った．なお，各対策の技術水準別採用は互いに独立であることを想定し，その組み合わせの比率を用いて定量化している．

照明器具については，地球温暖化対策計画[1]において 2020 年までに新築建築物の 100%で高効率照明が採用されていること，2030 年までに全ストックで高効率照明が採用されていることが想定されている．照明は蛍光灯・白熱灯などの既存照明技術と LED 照明の 2 水準を考慮した．照明工業会の自主統計[23)24]では照明器具別の出荷台数経変変化がまとめられている．そこで，LED とその他の照明の採用率を定量化し，新築・改修機会における技術採用率として用いた．改修については，竣工後，15 年に 1 回，照明の更新機会があると想定した．この結果，2030 年に 98%の建築物で LED が採用されていると推計されたことから，この想定は地球温暖化対策計画の技術普及想定と整合している．

トップランナー制度に基づき，複写機，プリンター，自動販売機等コンセント機器の2000年代から2010年代にかけての効率改善は30～40%[25]である．さらに，建築研究所[26]は2010年に30件の業務施設を対象としてコンセント機器の消費電力について実測調査を行い，各施設用途，室用途別の平均的なコンセント機器容量を算出している．本研究ではこれらの容量が2010年の業務施設ストックにおけるコンセント機器容量の実態を反映しているとして， 2010 年におけるコンセント機器容量を基準として2030年までに40%削減されると想定した．ここでは簡易的に，削減の有無の2水準を考慮し，LED照明を採用している施設はコンセント機器の消費電力も40%低いと想定した．

国土交通省では施行状況を把握するため，新築・改修業務施設における省エネルギー基準適合率や外皮基準適合率の推移[27]を公表している．外皮基準適合率と省エネルギー基準はほぼ同じ数字となっていることから，経年変化が記載されている省エネルギー基準の適合率に従って外皮基準を満たす断熱仕様を採用した建築物が竣工することを想定した．ただし，延床面積300 ㎡未満の建築物に関する実態データは公表されていないことから，300 ㎡未満の建築物と同じ比率を想定した．また，改修での断熱仕様の向上は考慮しなかった．

断熱仕様は建築研究所が開発しているモデル建物法入力支援ツール[28]にエネルギー需要推計に用いた代表モデル[29]（2.2.2 節参照）の条件を入力して BPIm 値の感度解析を行い，BPIm 値が 1 を下回る仕様を決定した．本研究で用いる業務施設モデルは外壁を気泡コンクリート造，外壁断熱材を硬質ウレタンフォーム[30]と想定しており，断熱材が寒冷地（北海道，東北地域）で 30㎜，東京で15㎜の場合に省エネルギー基準設定外壁仕様の熱貫流率を満たす．窓仕様については寒冷地の大規模ビルではLow-e 複層ガラス，寒冷地の中規模ビルと温暖地の大規模ビルでは複層ガラス，温暖地の中規模ビルでは単層ガラスとすることで外皮基準に適合可能であることがわかった．この結果から，寒冷地では規模や竣工年によらず全ての業務施設で外壁断熱材30㎜，寒冷地以外では 15㎜ が採用されるとし，窓仕様については表 1 のように想定した．以上のように想定した外壁，窓仕様に関する分布と前述の施設用途別，規模・業態別，地域別，竣工年代別延床面積総量の推移に基づいて，業務施設ストックの外壁・窓仕様採用状況経年変化を推計した．

表 1　窓仕様の想定

延床面積	竣工年代別ストック	
	2000 年以前	2001 年以後
2 万㎡未満	複層 6mm ガラス	寒冷地: Low-e 複層ガラス その他地域: 複層 6mm ガラス
2 万㎡以上	寒冷地: 複層 6mm ガラス その他地域: 単層 3mm ガラス	寒冷地: 複層 6mm ガラス その他地域: 単層 3mm ガラス

空調設備については中央・個別の別，熱源の燃料種別，機器種別，空調システム種別，省エネルギー手法採用区分を考慮した．推計方法の詳細は秋沢ら[7]に詳しい．推計では竣工設備データ[31]を用いて作成されたロジスティック回帰モデルにより竣工時，改修時の設備種別採用確率を算

出し，延床面積を採用確率により按分して設備種別床面積を算出した．ロジスティック回帰モデルは延床面積，暖房デグリーデー，人口密度，竣工年を説明変数としており，2.2.1 節に説明した延床面積を各説明変数により分類し，分類別の説明変数の値を説明変数に入力することで各分類の技術採用確率を定量化している．なお，2013 年以降竣工される建築物は，回帰モデルの仕様上 2010 年代に観測された建築物の技術採用傾向が適用される．これにより現行の省エネルギー基準は達成可能であることを確認している[29]ため，本設定は地球温暖化対策計画の想定と整合している．なお，改修は竣工後 25 年に 1 回行われることを想定し，中央熱源方式のシステムは中央熱源方式として，個別熱源方式のシステムは個別熱源方式として改修が行われることを想定している．

空調用熱源機器の効率はメーカーによる技術開発により経年的に上昇しており，また熱源の種類により効率は大きく異なる．本研究では，2010 年以前の推計(以下水準 1)では岡本[32]の推計によるストック平均定格 COP を，2018 年以降年の推計(以下水準 3)では国土技術政策総合研究所[33]が公表している 2018 年の新築・改修業務施設における熱源機器別平均定格 COP を用いた．2011～2017 年の推計(以下水準 2)は水準 1 と水準 3 の中間値の COP を用いた．本研究で想定した推計年別定格 COP を表 2 に示す．

表 2　推計年別定格 COP[-]の想定

熱源機器		推計年代別ストック		
		水準 1	水準 2	水準 3
ビル用マルチ	冷房	2.5	3.0	3.5
	暖房	3.1	3.5	4.0
ガスヒートポンプ	冷房	0.9	1.0	1.2
	暖房	1.1	1.2	1.4
吸収式冷凍機		1.0	1.1	1.3
空冷ヒートポンプ	冷房	2.9	3.2	3.6
	暖房	3.1	3.3	3.6
ターボ冷凍機		5.0	5.3	5.7

２．２．２　代表モデルの設計

次に，定量化したストック構成比率に基づいて代表モデルをサンプリングした．本研究では日本全国の対象業務施設を 1 万の代表モデルで代表させた．2013 年ケースでは各代表モデルは延床面積 125,500 ㎡を代表する．

建築仕様、フロアの使われ方に関する代表モデルの想定を表 3 に示す。代表モデルは各類型における平均的な形状を持つ業務施設である。また、事務所、宿泊施設、医療施設は建物の規模によって用途が複合化する傾向があることから、代表モデルではフロアを単位として表に示すフロア用途を想定し、照明、コンセント機器の消費電力、建物内在室者の在室密度、外気導入量を想定した。代表モデルの設計手法は Kim ら[29]に詳しい。

時刻別のエネルギー需要の推計において現実的な建物・設備の稼動条件を設定することは重要

である。本研究は第 5 回近畿圏パーソントリップ調査データに基づいて生成された建物利用者一人一人の移動、滞在スケジュールに基づいて機器・設備の稼働を決定する。照明、空調は滞在者がいる空間で稼働するものとし、コンセント負荷は滞在者数一人当たりの消費量を決定し、滞在時にその負荷が生じることを想定した[6)]。

表 3　代表モデルの仕様（CL1～CL9 は規模区分を示す）

<table>
<tr><th>用途</th><th>項目</th><th>CL1</th><th>CL2</th><th>CL3</th><th>CL4</th><th>CL5</th><th>CL6</th><th>CL7</th><th>CL8</th><th>CL9</th></tr>
<tr><td rowspan="4">事務所</td><td>延床面積 [m²]</td><td>132</td><td>349</td><td>726</td><td>1,447</td><td>3,258</td><td>7,089</td><td>13,873</td><td>31,238</td><td>190,202</td></tr>
<tr><td>基準階床面積 [m²]</td><td>66</td><td>116</td><td>182</td><td>289</td><td>543</td><td>1,013</td><td>1,734</td><td>2,840</td><td>6,559</td></tr>
<tr><td>階数</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>11</td><td>29</td></tr>
<tr><td>フロア用途</td><td colspan="5">事務所</td><td colspan="3">事務所、会議室、飲食店、小売店</td></tr>
<tr><td rowspan="4">宿泊</td><td>延床面積 [m²]</td><td>137</td><td>364</td><td>744</td><td>1,444</td><td>3,200</td><td>7,611</td><td>15,083</td><td>34,528</td><td>177,850</td></tr>
<tr><td>基準階床面積 [m²]</td><td>69</td><td>121</td><td>186</td><td>289</td><td>457</td><td>846</td><td>1,160</td><td>2,877</td><td>6,587</td></tr>
<tr><td>階数</td><td>2</td><td>3</td><td>4</td><td>5</td><td>7</td><td>9</td><td>13</td><td>12</td><td>27</td></tr>
<tr><td>フロア用途</td><td colspan="3">ロビー、客室</td><td colspan="4">同左＋飲食</td><td colspan="2">同左＋宴会場</td></tr>
<tr><td rowspan="4">医療福祉</td><td>延床面積 [m²]</td><td>136</td><td>330</td><td>701</td><td>1,455</td><td>3,238</td><td>7,597</td><td>14,696</td><td>31,309</td><td>104,835</td></tr>
<tr><td>基準階床面積 [m²]</td><td>68</td><td>110</td><td>234</td><td>364</td><td>648</td><td>1,266</td><td>2,449</td><td>4,473</td><td>6,989</td></tr>
<tr><td>階数</td><td>2</td><td>3</td><td>3</td><td>4</td><td>5</td><td>6</td><td>6</td><td>7</td><td>15</td></tr>
<tr><td>フロア用途</td><td colspan="3">診療室、待合室、処置室</td><td colspan="2">診療室、待合室、処置室、病室</td><td colspan="2">診療室、待合室、処置室、病室、飲食</td><td colspan="2">診療室、待合室、処置室、病室、ICU、飲食</td></tr>
</table>

２．２．３　代表モデルを用いたエネルギー需要推計

代表モデルを用いたエネルギー需要の推計にはアメリカ Department of Energy が開発している EnergyPlus 8.6[13)]を用いた。なお、気象条件は前述の地域区分に対応して札幌、仙台、東京、新潟、名古屋、新潟、大阪、広島、松山、福岡、沖縄の気象台で観測された 2013 年アメダスデータから作成した。なお，代表モデルを用いたエネルギー需要推計の精度評価は Yamaguchi ら[6)]において施設単位で日本サステナブル建築協会が公開している非住宅建築物のエネルギー消費データベース（DECC）[36)]，環境共創イニシアチブ（SII）[37)]が公開している時系列電力需要データと整合することを確認している.

２．２．４　エネルギー需要の積み上げ

前の手順で定量化された類型別延床面積あたりエネルギー需要原単位と、用途別・規模別の延床面積との積和を取ってストック全体のエネルギー需要を算出した。これにより地域別の業務施設集積状況、空調熱源システム採用状況、エネルギー需要の対応関係がエネルギー需要に反映される。

部門のエネルギー消費総量については山下ら[38]が評価し，ある程度妥当であることを確認している．

３．計算ケース

本研究では表 4 に示す 4 つのケースを想定し，民生家庭部門，業務部門のエネルギー消費量，CO_2排出量，電力需要の変化を推計する．2013 年ケース，2019 年ケースではそれぞれの部門のストック構成を想定し，2030 年ケースでは，2016 年に閣議決定された旧地球温暖化対策計画[35]に記述されている変化が実現された状況を想定した．2050 年ケースでは，脱炭素化に向けて，省エネルギー技術の最大限の普及，冷暖房，給湯用途における電化を想定した．2013 年ケースは 2013 年度の気象データとカレンダー（曜日の想定），それ以外のケースでは 2019 年度の気象データとカレンダーを用いた．

表 4　計算ケース

計算ケース	想定内容
2013 年	2013 年の社会を想定した．
2019 年	2019 年の社会を想定した．
2030 年	2016 年閣議決定の地球温暖化対策計画[35]に基づいて技術普及が起こることを想定した．
2050 年	冷暖房，給湯熱源の電化を想定した．また，利用可能な省エネルギー技術の全てが全ストックに採用されることを想定した．

３．１　家庭部門の想定

ケースの想定を表 5 に示す．2013 年ケース，2030 年ケースについては既報[7]に詳しい．2019 年ケースは 2013 年ケースと同様に設定した．2030 年ケースでは地球温暖化対策計画[35]に従い，LED 照明がストックの 100％の採用率となること，高効率給湯器が同計画に記載されている普及台数分採用されること，トップランナー基準による効率向上によりテレビ，冷蔵庫，エアコンの効率が向上することを想定した．また，同計画では住宅の熱性能について，1999 年の省エネルギー法改正で定められた基準（次世代基準）の適合率が 2030 年 30％となることを目標としており，住宅の新築・減失による時系列変化を考慮して同等のストック構成となるように設定した．

2050 年ケースでは次世代基準の採用率を 100％とした．また，暖房，給湯分野において電化が進展することを想定し，全世帯においてエアコン，ヒートポンプ（HP）給湯機により暖冷房，給湯が行われている状況を想定した．エアコンは現行販売機種のうち最高効率の機種が全世帯へ普及すること，HP 給湯機では稼働時刻を太陽光発電の発電量が大きい昼間に稼働することを想定した．これに加えて，家電機器については世帯当たりの保有数量を 1 台に制限することを想定した．

表 5　家庭部門における技術更新の想定

対策項目	2013 年度 2019 年度	2030 年度	2050 年度
断熱性能	2013 年度, 2019 年度ストックを想定	温対計画に倣い設定	次世代基準 100%
照明	蛍光灯 100%	LED 採用率 100%	同左
家電	2013 年ストックを想定	TV･冷蔵庫の効率の向上	機器数の制限
暖房機器	同上	2013 と同じ	エアコン　100%(現行機種最高効率)
給湯器	同上	温対計画に倣い設定	HP100%(昼間稼働)

３．２　業務部門の想定

業務部門の想定を表 6 に示す．照明については文献等に基づいて各業務施設の標準的な照明設備仕様を調査し，2013 年ケースの仕様を設定した．前述の通り LED 照明の採用比率の経年変化を算出し，竣工から 15 年に 1 回システム更新の機会があることを想定して各機会において当該年の LED 照明採用比率に従って LED 照明への更新が行われることを想定した．この想定により 2030 年までに 98%の床面積が LED 照明を採用する結果となった．2050 年ケースでは全照明が LED 照明に代替されていることを想定した．コンセント機器については，2030 年度において消費電力が 40%減少することを想定した．その間は簡易化のため，照明が代替された施設において 40%減少となるように設定した．建築物の断熱については竣工時に決定されることを想定し，前述の通り新築建築物の 1999 年省エネルギー基準達成率 [27] に応じて断熱が採用されることを想定した．ただし，寒冷地，延床面積 2 万㎡以上の建築物では断熱が採用されていることを想定した．また，改修での性能向上は考慮していない．空調・給湯設備については，竣工設備データを用いて作成されたロジスティック回帰モデルにより竣工時，改修時の設備種別採用確率を算出し，床面積を採用確率により案分して設備種別床面積を算出した．改修は竣工後 25 年に 1 回行われることを想定した．対象としたのは空調熱源種別・構成，空調システム種別，空調関連省エネルギー手法，給湯システム種別である．2030 年までは 2010 年代に観測された技術採用傾向が継続することを想定した．これは，2010 年代の技術採用傾向の延長により建築省エネルギー法の省エネルギー基準を満足することが可能であるためである [6]．ただし，秋沢ら [7] による推計において HP 給湯機の普及は限定的と推計されたことから，本研究では 2030 年までの HP 給湯機の大幅な普及は想定しなかった．2050 年ケースでは，局所給湯方式の電気式温水器を除いて全ての給湯器が HP 給湯機に代替されることを想定した．加えて，空調用熱源機器は竣工から 15 年に 1 回更新されることを想定した．熱源機器性能として 4 水準を想定し，経年的に設置時の効率が向上することを想定した [17]．

表 6　業務部門における技術更新の想定

対策項目	2013 年度 2019 年度	2030 年度	2050 年度
断熱性能	2013 年度, 2019 年度ストックを想定	2030 年度におけるストックを想定	全建築物において外壁・窓での断熱が採用されている
照明	同上	LED 採用率 100%	同左
コンセント機器	同上	2013 年度比 40%の効率向上	同左
空調	同上	2010 年代の技術採用傾向の延長	熱源機器の電化および省エネルギー手法の最大限の採用
給湯	同上	2010 年代の技術採用傾向の延長	熱源機器の電化

３．３　エネルギー供給システムの想定

CO_2 排出量の推計では，地球温暖化対策計画 [1]，地球温暖化対策推進本部による同計画進捗状況評価 [39] に合わせて電力の CO_2 排出係数を 2013 年ケースで 0.57 kgCO_2/kWh，2019 年度は 0.44 kgCO_2/kWh [39]，2030 年 0.25 kgCO_2/kWh とした．2050 年ケースは 2030 年と同じとした．電気以外は総合エネルギー統計に適用するエネルギー源別標準発熱量・炭素排出係数一覧表 [40] により与えた．なお，家庭部門は都市ガスと LP ガスを，業務部門では石油系燃料と都市ガスを区別しておらず，すべて都市ガスとして計算を行っている．

４．結果

４．１ 年間エネルギー消費及び CO_2 排出量

図 3 に年間一次エネルギー消費量の推計結果を示す．2013 年ケースでは家庭と業務部門の電力需要は同程度の数値となった．2013 年ケースと比較すると，2019 年ケースは 9%，2030 年ケースは 21%，2050 年ケースは 47%減少した．なお，業務部門ではすべての業態をカバーしていないため，削減率については注意が必要である．棒グラフ上の数字は CO_2 排出量[MtCO_2/年]を示す．2013 年から 2019 年までの削減量は 84 MtCO_2/年と推計された．この削減の主たる要因は電力排出係数の改善効果であるが，家庭部門，業務部門ともに各種対策の導入効果は地球温暖化対策計画進捗状況評価 [39] とある程度整合していることを確認している．2030 年ケースでは 186 MtCO_2/年が削減されると推計された．この削減量は両部門の 2030 年度削減目標合計値 260 MtCO_2/年の 72%に相当する．業務その他部門の排出量のうち本検討は 60%をカバーしているのみであるため，ある程度地球温暖化対策計画と整合した結果になっていると考えられる．2050 年の削減量は 246 MtCO_2/年と推計された．

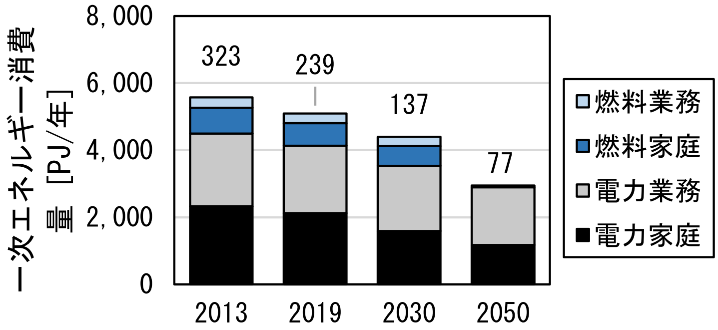


図 3　一次エネルギー消費量推計結果

このような変化となった要因を確認するため，図 4 に使用用途別の一次エネルギー消費量の内訳，図 5 に熱需要の推計結果を示す．ただし，業務部門の給湯用熱需要は定量化が間に合わなかったため，家庭部門のみの需要量を示している．図 4 をみると，すべての使用用途においてエネルギー消費が減少している．空調換気用エネルギー消費は一次エネルギー消費量に占める比率が高く，2030 年までの変化が他の用途と比較して小さい．これに対して 2050 年ケースでは，住宅・建築物の断熱性の向上，省エネルギー技術の最大限の利用，熱源の電化により，エネルギー消費量が大幅に減少した．図 5 に示す冷暖房用の熱需要では 2013 年と 2019 年の間に気象条件の差異に起因する冷暖比の差異があるものの，合計値は一貫して減少している．一次エネルギーベースのシステム COP(熱需要/空調換気用一次エネルギー消費量)を算出すると,2013 年ケースは 0.68, 2030 年ケースは 0.72，2050 年ケースは 1.17 である．家庭部門の給湯需要については図 5 からわかるように大きな変化はみられない．

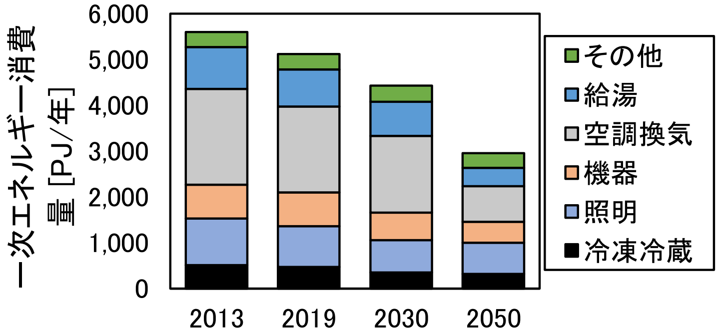


図 4　一次エネルギー消費量の用途別内訳

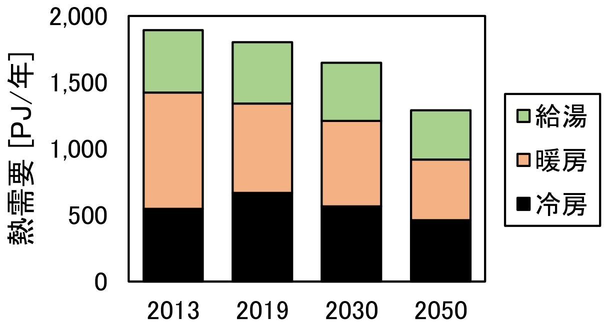


図 5　熱需要推計結果（業務の給湯を除く）

４．２　電力需要

図 6 に 2 月，5 月，8 月の月別時刻別平均電力需要の推計結果を示す．2013 年ケースとその他のケースでは気象条件が異なるので注意が必要である．8 月に注目すると，2019 年度から 2030 年度，2050 年度にかけて一貫して電力需要は減少した．これは各種対策によるエネルギー効率の改善によるものであり，昼間の時間帯における削減効果は 20GW オーダーである．5 月では 2050 年ケースにおいて，0 時から 6 時ごろまでの電力需要が 2030 年ケースより減少し，昼間の電力需要が増加した．これは，家庭用 HP 給湯機を PV 発電量が大きい昼間に稼働することを想定したためである．2 月は給湯における電化に加えて，暖房における電化の影響が含まれる．2050 年度の需要は HP 給湯機が稼働する昼間の一部の時間帯を除き，2030 年ケースの電力需要よりも小さい数値を示した．この結果は，熱用途熱源の電化による電力需要の増加が省エネルギーによるエネルギー効率の向上によって回避可能であることを示唆する．なお，2013 年度 2 月に顕著であるが，冬期は朝方に急峻な変動がみられる．これは業務部門における暖房用電力需要に起因するものであり，SII データとの比較ではこの時間帯は実態と乖離し，過大推計になっていることを確認した．したがって，冬期の朝方の時間帯の推計結果は誤差が大きいと考えられ，この点の改善は今後の課題とする．

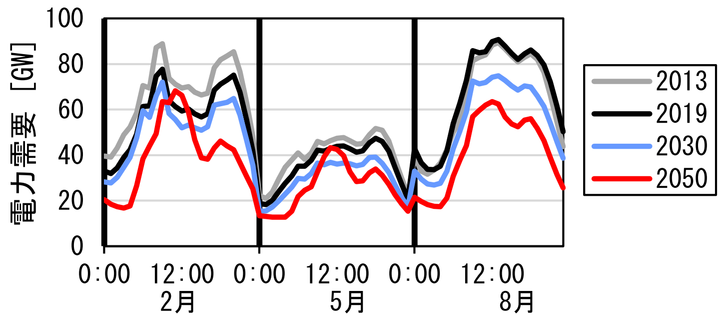


図 6　2 月，5 月，8 月の電力需要時刻別平均値推計結果

５．まとめ

本研究は我が国の民生家庭部門，業務部門を対象として 2030 年，2050 年を想定してエネルギ

一需要，CO_2排出量を推計した．推計モデルは住宅・業務施設ストックのストック構成をその多様性を含めて模擬し，エネルギー需要が決定される構造を人の行動から再現する方法を採用している．業務施設は排出量の60%をカバーするものであるが，地球温暖化対策計画で想定されている変化により2013年度比，2030年までに年間186 $MtCO_2$/年が削減されうること，2050年では省エネルギー技術が最大限利用され，熱用途の熱源が電化された場合，2030 年の電力排出係数目標0.25 $kgCO_2$/kWh の条件の下で246 $MtCO_2$/年が削減可能と推計された．2030年から2050年までは電力の排出係数を固定したにもかかわらず CO_2 排出量の削減は大きく，大きな削減ポテンシャルがあるといえる．特に，空調換気，給湯の熱用途の削減が大きく，現在検討されている建築物の省エネルギー基準の見直しなどの影響を含めて，削減の前倒し等の検討を行うことを今後の課題とする．電力需要については省エネルギーによるエネルギー効率の向上によって熱用途熱源の電化による電力需要の増加が回避可能であることを示した．

参考文献

1) 内閣官房：地球温暖化対策計画（2021年10月）
2) 松岡綾子，杉山みなみ，桃木貴志，下田吉之：長期エネルギー需給見通しにおける家庭部門CO2排出削減見込み量の検証, 日本建築学会環境系論文集, No. 84, Vol. 757(2019), pp. 323-333.
3) Taniguchi-Matsuoka A, Shimoda Y, Sugiyama M, Kurokawa Y, Matoba H, Yamasaki T, et al. Evaluating Japan’s national greenhouse gas reduction policy using a bottom-up residential end-use energy simulation model. Applied Energy 2020; 279: 115792. https://doi.org/10.1016/j.apenergy.2020.115792.
4) 杉山みなみ, 下田吉之, 山口容平: 家庭部門エネルギー需要シミュレーションによる 2050 年ゼロエミッション実現可能性の検討, 日本建築学会環境系論文集 85(770) 289 – 298 2020年4月, https://doi.org/10.3130/aije.85.289
5) Yoshiyuki Shimoda, Minami Sugiyama, Ryuya Nishimoto, Takashi Momonoki. Evaluating decarbonization scenarios and energy management requirement for the residential sector in Japan through bottom-up simulations of energy end-use demand in 2050, Applied Energy, No. 303, 117510 (2021), https://doi.org/10.1016/j.apenergy.2021.117510
6) Yamaguchi Y, Kim B, Kitamura T, Akizawa K, Chen H, Shimoda Y. Building stock energy modeling considering building system composition and long-term change for climate change mitigation of commercial building stocks. Applied Energy, No. 306, 117907 (2022). https://doi.org/10.1016/J.APENERGY.2021.117907.
7) 秋沢琴音, 山口容平, 金範埈, 鳴川公彬, 下田吉之: 業務部門における建築設備ストック経年変化のモデリング，エネルギー・資源学会論文誌，No. 41, pp. 318-327 (2020), https://doi.org/10.24778/jjser.41.6_318.
8) Sandberg, N. H., Næss, J. S., Brattebø, H., Andresen, I., & Gustavsen, A. Large potentials for energy saving and greenhouse gas emission reductions from large-scale deployment of zero emission building

technologies in a national building stock. Energy Policy, No. 152, 112114 (2021). https://doi.org/10.1016/j.enpol.2020.112114.

9) Langevin, J., Harris, C. B., & Reyna, J. L. Assessing the Potential to Reduce U.S. Building CO2 Emissions 80% by 2050. Joule, No. 3, pp. 2403–2424. (2019), https://doi.org/10.1016/j.joule.2019.07.013.

10) Hirvonen, J., Heljo, J., Jokisalo, J., Kurvinen, A., Saari, A., Niemelä, T., Sankelo, P., & Kosonen, R. Emissions and power demand in optimal energy retrofit scenarios of the Finnish building stock by 2050. Sustainable Cities and Society, No. 70, 102896 (2021). https://doi.org/10.1016/j.scs.2021.102896.

11) Boßmann T, Staffell I. The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain. Energy, No. 90, pp. 1317–33 (2015).
doi:10.1016/j.energy.2015.06.082.

12) Grubler A, Wilson C, Bento N, Boza-Kiss B, Krey V, McCollum DL, et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy, No. 36, pp. 515–27 (2018).
https://doi.org/10.1038/s41560-018-0172-6.

13) United States Department of Energy, EnergyPlus Ver.8.6, (2016). https://www.energyplus.net/.

14) 日本エネルギー経済研究所；EDMC エネルギー・経済統計要覧，(2017)，p.118，一般社団法人省エネルギーセンター.

15) 経済産業省：商業統計（2014）

16) 経済産業省：長期エネルギー需給見通し関連資料，p. 18. (2015)

17) 国土交通省: 建築着工統計調査

18) 鳴川公彬，山口容平，西島巧海，下田吉之：ストックの経年変化を考慮した業務部門地球温暖化対策計画評価，エネルギー・資源学会，第 38 回エネルギーシステム・経済・環境コンファレンス，6-3 (2022).

19) 国土交通省: 法人土地･建物基本調査（2013）

20) ESRI ジャパン: ArcGIS データコレクション詳細地図（2014）

21) 小見 康夫, 栗田 紀之: シナリオ分析による石膏ボードの排出量予測, 建物の長寿命化トレンドにおける建材のストック/排出量の算出手法に関する研究　その２, 日本建築学会計画系論文集, Vol.76, No.662 p. 835-841 2011

22) 国税庁: 2017 年 法定耐用年数表

23) 総合資源エネルギー調査会 : 省エネルギー・新エネルギー分科会省エネルギー小委員会 照明器具等判断基準ワーキンググループ(2017)照明器具等判断基準ワーキンググループ取りまとめ
https://www.meti.go.jp/shingikai/enecho/shoene_shinene/sho_energy/shomei_kigu/pdf/2016_01_03_00.pdf

24) 照明工業会自主統計（2021），照明器具の生産･出荷(販売)統計(2015 年度～2019 年度), https://jlma.or.jp/tokei/pdf/kigu_statistics01-2015-2019.pdf
25) 資源エネルギー庁: トップランナー機器の現状と今後の対応に関する整理（案）について, https://www.meti.go.jp/shingikai/enecho/shoene_shinene/sho_energy/pdf/009_04_00.pdf
26) 建築研究所：各種の業務用建築物における内部発熱に関する調査, https://www.kenken.go.jp/japanese/contents/publications/data/176/7.pdf
27) 国土交通省: 住宅・建築物のエネルギー消費性能の実態等に関する研究会とりまとめ, https://www.mlit.go.jp/common/001228937.pdf
28) 国土技術政策総合研究所: モデル建物法入力支援ツール（平成 28 年省エネルギー基準用）, https://model.app.lowenergy.jp/
29) B. Kim, Y. Yamaguchi, S. Kimura, Y. Ko, K. Ikeda, Y. Shimoda: Urban building energy modeling considering the heterogeneity of HVAC system stock: A case study on Japanese office building stock, Energy and Buildings, Vol.199(2019), pp.547-561
30) 国土技術政策総合研究所・建築研究所: 平成 25 年省エネルギー基準に準拠した算定・判断の方法及び解説 I 非住宅建築物
31) 一般社団法人建築設備技術者協会: 竣工設備データ集 （ELPAC）（1989-2017 年版）
32) 岡本ら；熱源機器の採用比率，機器効率の経年変化が近畿圏業務施設エネルギー需要に及ぼす影響の評価，第 31 回エネルギーシステム・経済・環境コンファレンス講演論文集，2015, p671-676
33) 国土技術政策総合研究所: 非住宅建築物の外皮･設備設計仕様とエネルギー消費性能の実態調査 - 省エネルギー基準適合性判定プログラムの入出力データの分析 -, http://www.nilim.go.jp/lab/bcg/siryou/tnn/tnn1107pdf/ks1107.pdf
34) EnergyPlus, https://energyplus.net/
35) 内閣官房：地球温暖化対策計画（2016 年 5 月）
36) 日本サステナブル建築協会;非住宅建築物の環境関連データベース 2006 年度～2008 年度データ
37) 環境共創イニシアチブ（SII）: Energy Management System Open DATA, https://www.ems-opendata.jp/ (2021)
38) 山下皓太郎，山口容平，大塚敦，西島拓海，鳴川公彬，下田吉之：業務部門における温室効果ガス排出量削減効果の評価：省エネルギー技術普及シナリオによる検討，エネルギー・資源学会，第 38 回エネルギーシステム・経済・環境コンファレンス，6-4 (2022).
39) 地球温暖化対策推進本部：2019 年度における地球温暖化対策計画の進捗状況(2021) https://www.env.go.jp/press/109430.html，アクセス日 2021 年 11 月 26 日
40) 資源エネルギー庁：エネルギー源別標準発熱量・炭素排出係数一覧表, https://www.enecho.meti.go.jp/statistics/total_energy/carbon.html，アクセス日 2021 年 11 月 26 日

Preparatory study for a model complementarity exercise on demand-side innovations for climate change mitigation

February 2022

Prepared for RITE
by Institute for Future Initiatives,
University of Tokyo

Summary

In order to achieve the goal of limiting the temperature rise to 1.5 degrees Celsius, as stated in the Paris Agreement and the Glasgow Climate Pact, a combination of various measures will be required in addition to the traditional energy supply-side measures such as the expansion of renewable energy. Of these, demand-side measures (e.g., energy demand reduction by sufficiency or efficiency) have rapidly gained attention in recent years. Unlike supply-side measures, demand-side measures are heterogeneous, and it is necessary to consider the differences among industry, buildings, and transport sectors, and to take into account the differences among options. In addition, since energy demand varies greatly by culture and region, it is crucial to examine the differences by geography when developing specific policies. Therefore, research itself is a huge challenge with respect to demand-side options.

Scenario analysis of demand-side measures has been increasingly conducted. However, this strand of research is still at an early stage and quite small despite its importance, compared to the supply-side research. In particular, exploration of uncertainty is an important issue.

In the field of long-term climate and energy policy research, scenario analysis based on quantitative models has been conducted for many years to support climate mitigation decision making under uncertainty. Given the differences in model results among research institutes, a number of international reports and projects, such as the Intergovernmental Panel on Climate Change (IPCC), have been conducted to compare multiple models with each other. However, no such research project has yet been conducted on the demand side. Moreover, the fundamental question remains whether it is possible to meaningfully compare demand-side scenarios since models that focus on demand-side options are heterogeneous.

At the annual meeting of the Energy Demand changes Induced by Technological and Social innovations (EDITS) community in December 2020, the participants agreed that a new modeling analysis called model complementary exercise (MCE), not a traditional model intercomparison project (MIP), would be useful. However, both the theoretical and practical aspects have not been explored yet.

This report presents initial thoughts on a proposed MCE. After briefly reviewing past MIP activities and making a comparison with the climate science community, the report describes an attempt for the first step of the MCE. In fact, it is not an MCE but rather a preliminary analysis based on the already existing scenario analyses, which would then inform the MCE design in the coming years.

In this paper, we first attempted to consider the theoretical aspect of MCE. Unlike climate science, there is no natural hierarchy or interrelationship of models for energy modeling, precluding a framework that can accommodate different models in a natural, organized manner. In search of practical guidance, a preliminary study was conducted to examine the MCE. Data was collected from modeling teams that had already produced low energy demand scenarios, though the data was not harmonized or standardized.

First, it is important to note that low demand scenarios have been implemented in multiple models. Several studies have quantified scenarios of reduced energy demand based on the original LED narrative. While the actual implementation varies widely from model to model and team to team, it is important to note that none of the models or teams found any fundamental problems.

Secondly, it was also found that the actual low-demand scenarios vary widely among modeling teams. This partially has to do with the lack of the standardized data collection. We didn't use an IPCC-like data collection based on the IAMC data template, and the results shown here might have been comparing apples to oranges. Variables for the passenger transport, for instance, vary greatly from one model to another. This motivates the standardization of the data collection procedure.

The fact that there are differences between models serves as a motivation for MCE. However, it is important to understand what kind of model structure and which parameter has caused such identified differences. This will be a research topic for the next year and beyond.

Summary of updates on the modelling tools and outputs to be used by the EDITS network

The project has received funding from the Research Institute of Innovative Technology for the Earth (RITE) under subcontract agreement D06710.

The International Transport Forum

The International Transport Forum is an intergovernmental organisation with 62 member countries. It acts as a think tank for transport policy and organises the Annual Summit of transport ministers. ITF is the only global body that covers all transport modes. The ITF is politically autonomous and administratively integrated with the OECD.

The ITF works for transport policies that improve peoples' lives. Our mission is to foster a deeper understanding of the role of transport in economic growth, environmental sustainability and social inclusion and to raise the public profile of transport policy.

The ITF organises global dialogue for better transport. We act as a platform for discussion and pre-negotiation of policy issues across all transport modes. We analyse trends, share knowledge and promote exchange among transport decision-makers and civil society. The ITF's Annual Summit is the world's largest gathering of transport ministers and the leading global platform for dialogue on transport policy.

The Members of the Forum are: Albania, Armenia, Argentina, Australia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Chile, China (People's Republic of), Croatia, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, India, Ireland, Israel, Italy, Japan, Kazakhstan, Korea, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Mexico, Republic of Moldova, Mongolia, Montenegro, Morocco, the Netherlands, New Zealand, North Macedonia, Norway, Poland, Portugal, Romania, Russian Federation, Serbia, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Tunisia, Turkey, Ukraine, the United Arab Emirates, the United Kingdom, the United States and Uzbekistan.

International Transport Forum
2 rue André Pascal
F-75775 Paris Cedex 16
contact@itf-oecd.org
www.itf-oecd.org

Acknowledgements

This report and the underlying work are part of the International Transport Forum's efforts to contribute to the Energy Demand changes Induced by Technological and Social innovations (EDITS) research community. They were funded by the Research Institute of Innovative Technology for the Earth (RITE) under subcontract agreement D06710.

Luis Martinez coordinated the report drafting. He and Mallory Trouvé authored the report.

Table of contents

Acknowledgements 3
Introduction 7
  Background 7
ITF scenario development 9
  Three policy scenarios for transport 9
ITF global urban passenger model assessment framework 11
  Demand transformative phenomena modelling 11
  Demand transformative phenomena assumptions in the tested narratives 13
  Main results for the tested scenarios 16
ITF global non-urban passenger model assessment framework 21
  Demand transformative phenomena modelling 21
  Demand transformative phenomena assumptions in the tested narratives 23
  Main results for the tested scenarios 25
ITF global freight model assessment framework 29
  Demand transformative phenomena modelling 29
  Demand transformative phenomena for assumptions in the tested narratives 31
  Main results for the tested scenarios 33

Tables

Table 1. Model implementation of policy measures / phenomena for urban passenger transport 12
Table 2. Scenario specifications for urban passenger transport 13
Table 3. Model implementation of policy measures / phenomena for non-urban passenger transport... 22
Table 4. Scenario specifications for non-urban passenger transport.. 23
Table 3. Model implementation of policy measures / phenomena for freight transport 30
Table 5. Scenario specifications for freight transport 31

Figures

Figure 1. Scheme of urban passenger model components 11
Figure 2. Demand for urban passenger transport, by mode 16
Figure 3. Average urban passenger trip mode shares by distance, in 2050 16
Figure 4. Demand for urban passenger transport, by region 17
Figure 5. Per capita demand for urban passenger transport, by region 17
Figure 6. CO_2 emissions from urban passenger transport, by mode... 18
Figure 7. Evolution of tank to wheel vs. well to tank CO_2 emissions from urban passenger transport...... 18
Figure 8. CO_2 emissions from urban passenger transport, by region.. 19
Figure 9. Per capita CO_2 emissions from urban passenger transport, by region...................................... 19
Figure 10. Pollutant emissions from urban passenger transport, by region 20
Figure 11. Non-urban passenger model scheme 21
Figure 12. Demand for non-urban passenger transport, by sub-sector... 25
Figure 13. Average non-urban passenger mode shares... 25
Figure 14. Demand for non-urban passenger transport, by region 26
Figure 15. Per capita demand for non-urban passenger transport, by region... 26
Figure 16. CO_2 emissions from urban passenger transport, by mode 27
Figure 17. Evolution of tank-to-wheel vs. well-to-tank CO_2 emissions from non-urban passenger transport 27
Figure 18. CO_2 emissions from non-urban passenger transport, by region 28
Figure 19. Per capita CO_2 emissions for non-urban passenger transport, by region 28
Figure 20. Model components.. 29

Figure 21. Import related transport activity 33
Figure 22. Projected Freight transport activity by mode 34
Figure 23. Freight transport emissions by mode 34
Figure 24. Carbon intensity of freight transport activity by mode 35
Figure 25. Surface freight emissions by region 35
Figure 26. Tank-to-wheel (TTW) and Well-to-tank (WTT) freight transport emissions 36

Introduction

This report summarises a contribution of the ITF to the Energy Demand changes Induced by Technological and Social innovations (EDITS) research community. It aims to analyse how demand disruptions in the transport sector have been incorporated in the ITF modelling framework. This contribution supports the assessment and creation of a common communication framework with global energy models such as the IIASA MESSAGE model.

The report presents how each policy or demand transformative element is incorporated into models: global urban passenger model, global non-urban passenger model and global freight model. The report summarises three narratives created by ITF that set the future development of some demand disruptive phenomena in different world regions for the next 30 years.

Background

EDITS carries out research to assure the transfer of methodological and modelling innovations across demand-side modes and builds an interactive research and policy network. The project identifies gaps and potentials to enhance novel service delivery models or policy interventions on climate mitigation and the SDGs.

Because of the high heterogeneity of consumers and the multitude of demand types (food, shelter, mobility, communication, etc.), the theoretical understanding and modelling of "demand" (outside aggregated simplistic formulation) remains limited and fragmented, as are resulting capabilities to propose and to assess demand-side policy interventions from the twin angle of climate mitigation as well as of promoting the SDGs.

The main objectives of EDITS are:

- to create a research community focusing on end-use, demand-side perspectives that further dialogue and crocross-fertilisation research and policy analysis through the sharing of novel data, novel concepts, methodologies and policy analyses.
- to improve the state-of-art of demand modelling in environmental and climate policy analysis, via methods and model inter comparisons and assisting the transfer of conceptual and methodological improvements across disciplines, sectors, and environmental domains.
- to better inform policy via structured model experiments and simulations that assess potential impacts, barriers, as well as synergies and trade-offs to other SDG objectives of demand-side policy interventions, particularly in novel fields and service provision models such as digitalisation, sharing economy, or the integration of SDG and climate objectives in synergistic policy designs.

EDITS focuses on both the human and the technical resources by launching an expert network and a demand-side model comparison exercise.

ITF is providing expertise and contributing in the transport sector by providing state of the art and practice tools, and insights into the role of innovations and policies for controlling or reducing transport activity, the derived energy consumption and CO2 emissions.

As part of this contribution, this report investigates how disruptive demand phenomena can be incorporated into existing modelling tools. This work will help the Transport Working Group of EDITS to increase data inputs into global energy assessment models.

The International Transport Forum has developed a set of modelling tools to build its forward-looking scenarios of transport activity. Covering all modes of transport, freight and passenger, the tools are unified under a single framework.

The ITF framework first estimates the demand for transport based on a set of socio-economic drivers (population, Gross Domestic Product, trade, etc.) before analysing how this demand may be satisfied. This second step includes a detailed mode choice sub model. Finally, the model computes the activity and the generated CO2 emissions related to transport. Additionally, other transport-related variables and indicators are produced depending on the sector, such as accessibility, connectivity, or resilience.

The ITF framework can assess the effect of an extensive range of policies and exogenous impacts. In all models, policies that may impact transport demand or the related CO2 emissions become input parameters. The models are constantly being worked on, improved and updated. None of the models relies on commercial (transport) modelling software, and they are developed entirely in-house. The most recent model documentation was developed under the Decarbonising Transport in Europe project in early 2020 and is available here (https://www.itf-oecd.org/itf-modelling-framework).

ITF scenario development

The ITF work was built under three different narratives or scenarios to generate a "What if" analysis about the main demand transformative phenomena tested.

Three policy scenarios for transport

The *Recover*, *Reshape* and *Reshape+* scenarios assess the impacts of different policy pathways on global transport demand, greenhouse gas emissions (reported as CO_2 equivalents), and other indicators, including local pollutant emissions, accessibility, and resilience (depending on the sector), up to 2050. The emissions are based on transport activity and do not include emissions from vehicle production or construction and operation of transport infrastructure. The three scenarios represent increasingly ambitious efforts by policymakers to decarbonise the transport sector while also meeting the UN Sustainable Development Goals (SDGs). All scenarios account for the Covid-19 pandemic by including the same baseline economic assumptions for the pandemic's impacts. Uncertainty surrounds its economic fallout, the behavioural shifts it may trigger, and the extent to which it will affect transport supply and travel patterns both in the long and short term. The ITF models use middle-of-the-road assumptions that lie somewhere between the most optimistic and most pessimistic forecasts available at the time of modelling.

For GDP and trade in 2020, the ITF models assume a drop in all world regions, based on the International Monetary Fund's World Economic Outlook June update (IMF, 2020) and the World Trade Organization's Trade Statistics and Outlook (WTO, 2020) applied to baseline GDP and trade values from the OECD ENV-Linkages model (Chateau et al., 2014). Following years assume the previous country-specific growth rates after 2020. This is approximated by a five-year delay in GDP and trade projections compared to pre-Covid-19 levels from 2020 onwards. Assumptions of economic activity and trade are held constant between all scenarios to better compare the true transport policy impact on activity, CO_2 emissions and other outcomes. Air connectivity growth is also adjusted, to account for the severity of the pandemic's impact on aviation. For 2020, ITF models assume a drop in flight frequencies and pre-Covid-19 growth rates to meet the projections for 2025 by the International Air Transport Association (IATA, 2020).

In *Recover*, governments prioritise economic recovery by reinforcing established economic activities. They continue to pursue existing (or imminent) commitments to decarbonise the transport sector from before the pandemic. Alongside these, governments take action with policies that ensure some of the transport trends that hinder decarbonisation observed during Covid-19 revert back to previous patterns by 2030. These trends include a shift to greater private car use, and reduction in public transport ridership, for example. Changes in behaviour such as reduced business travel or greater shifts to active mobility, which have lowered CO_2 emissions, also revert back to pre-pandemic norms by 2030.

In the *Reshape* scenario represents a paradigm shift for transport. Governments adopt transformational transport decarbonisation policies in the post-pandemic era. These encourage changes in the behaviour of transport users, uptake of cleaner energy and vehicle technologies, digitalisation to improve transport efficiency, and infrastructure investment to help meet environmental and social development goals. As in Recover, the Reshape scenario also assumes that transport trends and patterns observed during the pandemic revert back to previous patterns by 2030.

In *Reshape+*, governments seize decarbonisation opportunities created by the pandemic, which reinforce the policy efforts in *Reshape*. Measures reinforce changes in travel behaviour observed during the pandemic, such as reducing business travel or encouraging walking and cycling. Some of these policies are fast-tracked or implemented more forcefully than in *Reshape*. The scenario assumptions also include pandemic impacts on non-transport sectors that may nevertheless influence transport, for instance a regionalisation of trade as a result of near-sourcing to improve resilience. Under Reshape+, CO_2 emission targets for the transport sector can be achieved sooner and with more certainty, and with less reliance on CO_2 mitigation technologies whose efficacy is still uncertain.

The *Reshape* and *Reshape+* scenarios show what is possible with technologies and policies available today, but with increased investments and more political ambition. The policies act additively, meaning that while there are adjustments made for regions, most policies are applied to most regions with some adjustment for regional contexts. Results are not prescriptive in assigning certain combinations of measures to specific regions. The results show what is technically feasible under full implementation, but it is recognised that there may be political and financial constraints that require prioritisation of measures depending on local contexts. The policy scenarios show what may happen at the global and regional level under a set of policies to manage transport demand, shift to more sustainable modes, and improve energy efficiency of vehicles and fuels.

ITF global urban passenger model assessment framework

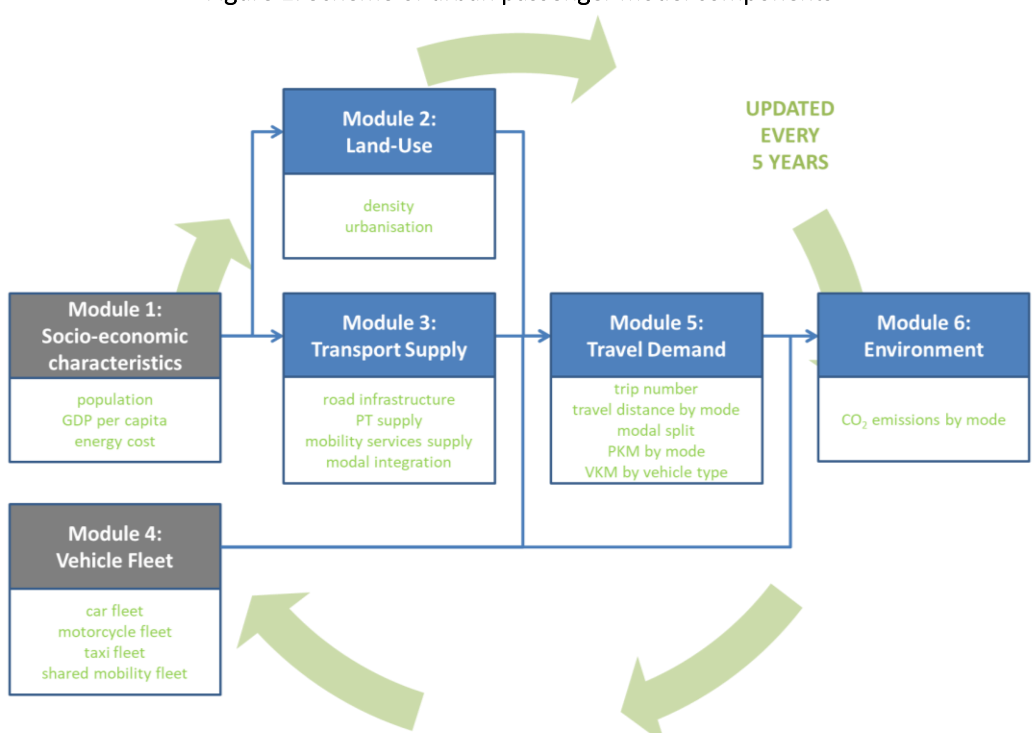
Demand transformative phenomena modelling

The ITF global urban passenger transport model is a strategic tool to test the impacts of policies and technology trends on urban travel demand, related CO2 emissions and accessibility indicators. Outputs for various scenarios can be obtained to 2050. The model represents passenger mobility at the scale of Functional Urban Areas (FUAs).

The model is designed as a systems dynamic model (stock and flow model) to evaluate the development of urban mobility in all cities over 50 000 inhabitants around the world. It combines data from various sources that form one of the most extensive databases on global city mobility to account for fifteen transport modes. These range from the conventional private car and public transport to new alternative modes such as shared mobility.

The urban passenger model represents travel behaviour by modelling aggregate travel behaviour by traveller segment. A traveller segment is defined by socio-economic characteristics of travellers (e.g. their gender, income level and age). While the model is built at the FUA level, the final analysis is carried out for nine world regions.

Figure 1. Scheme of urban passenger model components



Source: ITF.

A more recent and detailed presentation of this model is available in another dedicated output of the project (The 2020 global urban passenger transport model of the International Transport Forum).

The modelling approach to the measures or phenomena considered in the model that may impact urban transport activity and derived energy consumption and emissions in the next decades is presented in Table 1.

Table 1. Model implementation of policy measures / phenomena for urban passenger transport

Measure/Phenomena	Description	Implementation in the model
	Economic instruments	
Carbon pricing	Pricing of carbon-based fuels based on the emissions they produce.	Implements differentiated road pricing on mode choice.
Road pricing	Charges applied to motorised vehicles for the use of road infrastructure.	Implements differentiated road pricing on mode choice.
Parking pricing and restrictions	Regulations to control availability and price of parking spaces for motorised vehicles.	Increases the car cost in mode choice model.
	Enhancement of Infrastructure	
Land-use planning	Densification of cities.	Increases urban density, reduces PT access time in mode choice model.
Transit Oriented Development (TOD)	Increase in mixed use development in neighbourhoods around public transport hubs.	Increases urban density near heavy PT stations, reducing access time and average number of transfers in mode choice model
Public transport priority measures and express lanes	Prioritising circulation of public transport vehicles in traffic through signal priority or express lanes.	Increases speed in road based public transport modes. The update is reflected in model choice model travel time attribute.
Public transport service improvements	Improvements to public transport service frequency and capacity.	Increases speed in road based public transport modes. The update is reflected in model choice model travel time attribute.
Public transport infrastructure improvements	Improvements to public transport network density and size.	Decrease of the average access and waiting time, as well as the number of transfers in the mode choice model.
Integrated public transport ticketing	Integration of public transport ticketing systems.	Increases the alternative specific constant of PT modes and decrease cost in the mode choice model.
Bike and Pedestrian infrastructure improvements	Increase in dedicated infrastructure for active mobility.	Implements a bike infrastructure supply in the model affecting mode choice attributes (speed and alternative specific constant).
Speed limitations	Traffic calming measure to reduce speed and dominance of motor vehicles through low-speed zones or infrastructure.	Decreases speed / utility value of associated modes.
	Regulatory instruments	
Urban vehicle restriction scheme	Car restriction policies in certain areas and during certain times to limit congestion. Typically applied in the city centre.	Decreases car supply and ICE vehicle type share reducing car availability in mode choice model.
Low emission vehicles incentives and infrastructure investment	Incentives for the purchase and use of alternative fuel vehicles.	Increases car use cost and reduces car average age. Increases car travel distances affecting mode choice model.
	Stimulation of innovation and development	
Electric/alternative fuel vehicle penetration	Degree of uptake of electric/alternative vehicles in urban vehicle fleet	Adapt car based modes costs in the mode choice mode and modal carbon intensities.
Car sharing incentives	Incentives to encourage car rental schemes where members have access to a pool of cars as needed, lowering car ownership	Increases shared modes density, decreases the average car age, the shared mode cost and waiting time.
Carpooling policies	Carpooling policies encourage consolidating private vehicle trips with similar origins and destinations.	Increases the car load factor, reduces car use cost.
Ride sharing/shared mobility	Increased ridership in non-urban road transport (car & bus)	Increases car load factor and travel distance while decreasing average car age.
Mobility as a Service (MaaS) and multimodal travel services	Improved integration between public transport and shared mobility (app integration, as well as physical infrastructure, ticketing and schedule integration). Increase in availability and load factors of shared mobility	Increases shared modes supply and utility in mode choice model.

Exogenous factors		
Autonomous vehicles*	Introduction of vehicles with level 5 autonomous capabilities	Adapt mode costs and value of time of private car utility in mode choice model.
Teleworking	Reduces business and commuting trips, while increasing short non-work trips.	Decreases the elasticity of trip generation.

Demand transformative phenomena assumptions in the tested narratives

ITF has implemented the model to the three described narratives/scenarios. Table 2 presents the details of the scenario specification, the range of implementation across world regions and the calendar of assumptions of measures or phenomena that affect the urban transport demand and derived energy consumption and emissions.

Table 2. Scenario specifications for urban passenger transport

Measure/Exogenous Factor	Description	Recover	Reshape	Reshape+
Economic instruments				
Carbon pricing	Pricing of carbon-based fuels based on the emissions they produce.	Carbon pricing varies across regions: 150 to 250 USD per tonne of CO_2 in 2050	Carbon pricing varies across regions: 300 to 500 USD per tonne of CO_2 in 2050	
Road pricing	Charges applied to motorised vehicles for the use of road infrastructure.	0% to 7.5% increase of non-energy related car use costs by 2050, half for motorcycles.	2.5% to 25% increase of non-energy related car use costs by 2050, half for motorcycles.	
Parking pricing and restrictions	Regulations to control availability and price of parking spaces for motorised vehicles.	5% to 50% of city area subject to parking constraints, and 0% to 60% increase in parking prices by 2050.	7% to 75% of city area subject to parking constraints and 20% to 150% increase in parking prices by 2050.	
Enhancement of Infrastructure				
Land-use planning	Densification of cities.	Density variation of -10% to +20% for the city centre of urban areas over 300 000 inhabitants. Density variation of -10% to +10% for cities under 300 000 inhabitants and for suburbs of urban areas over 300 000 inhabitants.	Density variation of 0% to +40% for the city centre of urban areas over 300 000 inhabitants. Density variation of 0% to +20% for cities under 300 000 inhabitants and for suburbs of urban areas over 300 000 inhabitants.	
Transit Oriented Development (TOD)	Increase in mixed use development in neighbourhoods around public transport hubs.	Increases the land-use diversity mix and increases the accessibility to public transit of 5% by 2050.	Increases the land-use diversity mix and increases the accessibility to public transit of 7.5% by 2050.	Increases the land-use diversity mix and increases the accessibility to public transit of 10% by 2050.
Public transport priority measures and express lanes	Prioritising circulation of public transport vehicles in traffic through signal priority or express lanes.	0% to 40% of bus, light rail transit and bus rapid transit network prioritised by 2050.	10% to 60% of surface public transport network prioritised by 2050.	
Public transport service improvements	Improvements to public transport service frequency and capacity.	-10% to +10% service improvement for rail or corridor based public transport systems resulting	10% to 15% service improvement for rail or corridor based public transport systems resulting in a 1% to 1.5% speed variation by 2050. 20% to 50%	

		in a -1% to +1% speed variation by 2050. 10% to 30% service improvement for bus and paratransit transport systems resulting in a 0.25% to 0.7% speed variation by 2050.	service improvement for bus and informal public transport systems resulting in a 0.5% to 1.25% speed variation by 2050.	
Public transport infrastructure improvements	Improvements to public transport network density and size.	0% to 100% growth increase for the public transport network by 2050.	0% to 200% growth increase for the public transport network by 2050.	
Integrated public transport ticketing	Integration of public transport ticketing systems.	1.5% to 4.5% reduction of public transport ticket cost, and 2.5% to 7.5% reduction of public transport monthly subscription cost by 2050.	1.5% to 7.5% reduction of public transport ticket cost, and 2.5% to 12.5% of public transport monthly subscription cost by 2050.	
Bike and Pedestrian infrastructure improvements	Increase in dedicated infrastructure for active mobility.	20% to 300% increase in road space available to active modes by 2050 and simultaneous increase in speed of active modes, including micromobility	40% to 500% increase in road space available to active modes by 2050 and simultaneous increase in speed of active modes, including micromobility.	50% to 600% increase in road space available to active modes by 2050 and simultaneous increase in speed of active modes, including micromobility.
Speed limitations	Traffic calming measure to reduce speed and dominance of motor vehicles through low-speed zones or infrastructure.	2% to 30% reduction of speed on main roads, by 2050	5% to 50% reduction of speed on main roads, by 2050	
Regulatory instruments				
Urban vehicle restriction scheme	Car restriction policies in certain areas and during certain times to limit congestion. Typically applied in the city centre.	0% to 17.5% reduction of car ownership by 2050, Reduction of the car and car sharing speeds while increasing the car and motorcycle access time.	3.5% to 25% reduction of car ownership by 2050, Reduction of the car and car sharing speeds while increasing the car and motorcycle access time.	
Low emission vehicles incentives and infrastructure investment	Incentives for the purchase and use of alternative fuel vehicles.	Decreases average vehicle-kilometres made with diesel, gasoline and methane fuels between 0% and 4% by 2050.	Decreases average vehicle-kilometres made with diesel, gasoline and methane fuels between 0% and 36 % by 2050.	Decreases average vehicle-kilometres made with diesel, gasoline and methane fuels between 0% and 45% by 2050.
Stimulation of innovation and development				
Electric/alternative fuel vehicle penetration	Degree of uptakeof electric/alternative vehicles in urban vehicle fleet	Follows the IEA NPS Scenario	Follows the IEA SDS Scenario	
Car sharing incentives	Incentives to encourage car rental schemes where members have access to a pool of cars as needed, lowering car ownership	0% to 15% increase in shared car availability per capita, and 0% to 40% increase in shared motorcycle availability per capita, by 2050.	5% to 30% increase in shared car availability per capita, and 10% to 60% increase in shared motorcycle availability per capita, by 2050.	

Carpooling policies	Carpooling policies encourage consolidating private vehicle trips with similar origins and destinations.	3.5% to 8.3% increase in average load factor by 2050.	7.6% to 16.7% increase in average load factor by 2050.	
Ride sharing/shared mobility	Increased ridership in non-urban road transport (car & bus)	25% to 200% increase of ride sharing vehicles per capita growth by 2050. Load factor evolution from -50% to +25% by 2050.	25% to 300% increase of ride sharing vehicles per capita growth by 2050. Load factor increase from 0% to 100% by 2050.	
Mobility as a Service (MaaS) and multimodal travel services	Improved integration between public transport and shared mobility (app integration, as well as physical infrastructure, ticketing and schedule integration). Increase in availability and load factors of shared mobility	1.7% to 10% reduction of public transport ticket cost, and 1.0% to 6.0% reduction of shared mobility cost by 2050. Increase in number of shared mobility vehicles and stations	3.3% to 20% reduction of public transport ticket cost, and 2.0% to 12.0% reduction of shared mobility cost by 2050. Significant increase in number of shared mobility vehicles and stations	
Exogenous factors				
Autonomous vehicles*	Introduction of vehicles with level 5 autonomous capabilities	The percentage of autonomous vehicles in use varies across regions: for car 0% to 3%, for bus 0% to 1.5%, for shared vehicles 0 to 6%.		
Teleworking	Reduces business and commuting trips, while increasing short non-work trips.	2.5% to 20% of the active population could telework by 2050.	3.5% to 30% of the active population could telework by 2050.	5% to 40% of the active population could telework by 2050.

Note: Range of values reflect the varying degrees of implementation of policy measures across the different world regions in each scenario.

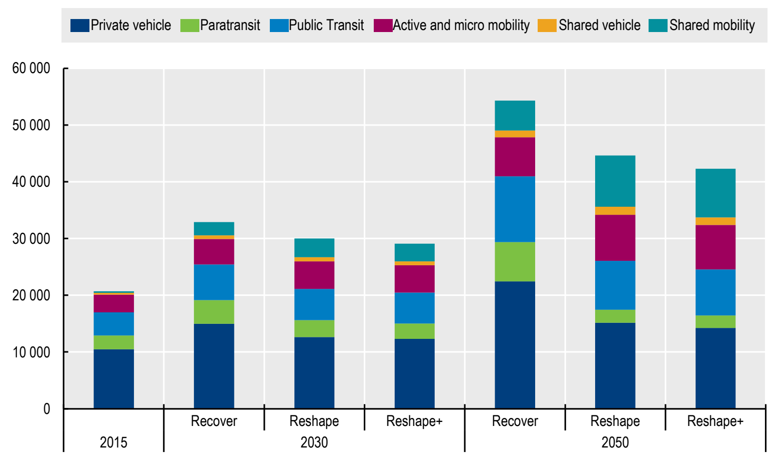
*Autonomous vehicles are considered but are not a primary factor in any of the scenarios. All scenarios assume a constant level of introduction of vehicles with Level 5 autonomy. The *ITF Transport Outlook 2019* focussed more specifically on transport disruptions, including autonomous vehicles, and assessed related scenarios.

Main results for the tested scenarios

The narratives and scenarios designed by ITF for the ITF 2021 Outlook lead to three different future outcomes. The next figures and tables describe some of them. A detailed analysis at the country level can be performed in the detailed dataset provided in the annexe to this report.

Figure 2. Demand for urban passenger transport, by mode

Billion passenger-kilometres

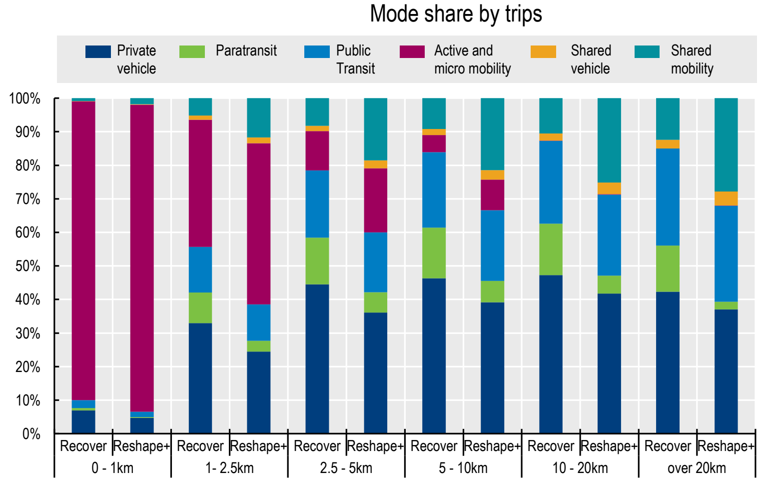


Note: Note: Active and micromobility includes walking, biking, scooter sharing, and bike sharing. Public transport includes PT rail, metro, bus, LRT, and BRT. Paratransit includes informal buses and PT three-wheeler. Shared vehicle includes motorcycle and car sharing. Private Vehicle includes motorcycles and cars. Shared mobility includes taxis, ride sharing, and taxi buses.

Source: ITF modelled estimates

Figure 3. Average urban passenger trip mode shares by distance, in 2050

Mode share by trips

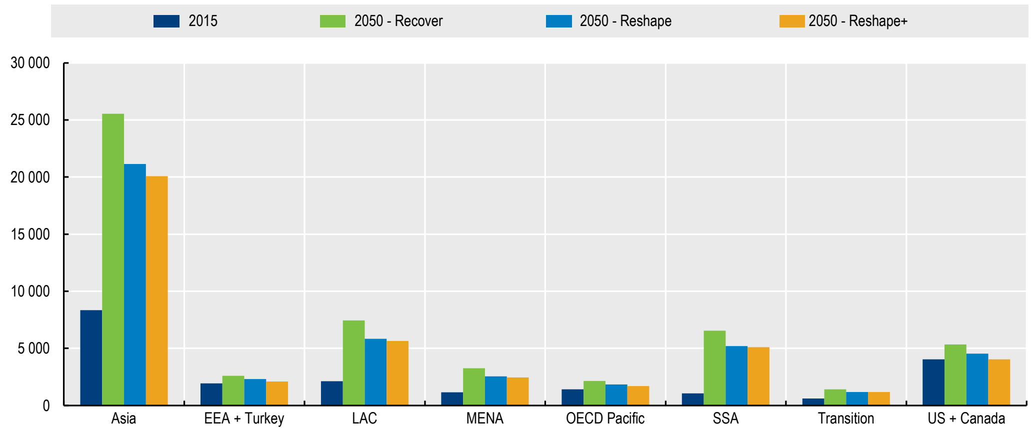


Note: *Reshape* results in very similar trip-based mode shares as *Reshape+*, therefore it is not pictured separately. Active and micromobility includes walking, biking, scooter sharing, and bike sharing. Public transport includes PT rail, metro, bus, LRT, and BRT. Paratransit includes informal buses and PT three-wheeler. Shared vehicle includes motorcycle and car sharing. Private Vehicle includes motorcycles and cars. Shared mobility includes taxis, ride sharing, and taxi buses.

Source: ITF modelled estimates

Figure 4. Demand for urban passenger transport, by region

Billion passenger-kilometres

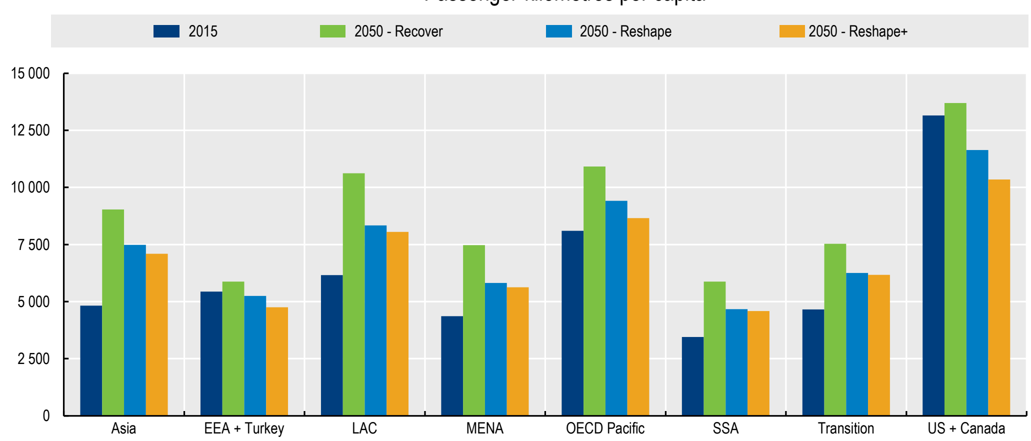


Note: EEA refers to the European Economic Area. LAC refers to Latin America and the Caribbean. MENA refers to the Middle East and North African countries. OECD Pacific countries include Australia, Japan, New Zealand and South Korea. SSA refers to Sub Saharan Africa. Transition economies include countries that were part of the Former Soviet Union and non-EU south-eastern European countries.

Source: ITF modelled estimates

Figure 5. Per capita demand for urban passenger transport, by region

Passenger-kilometres per capita

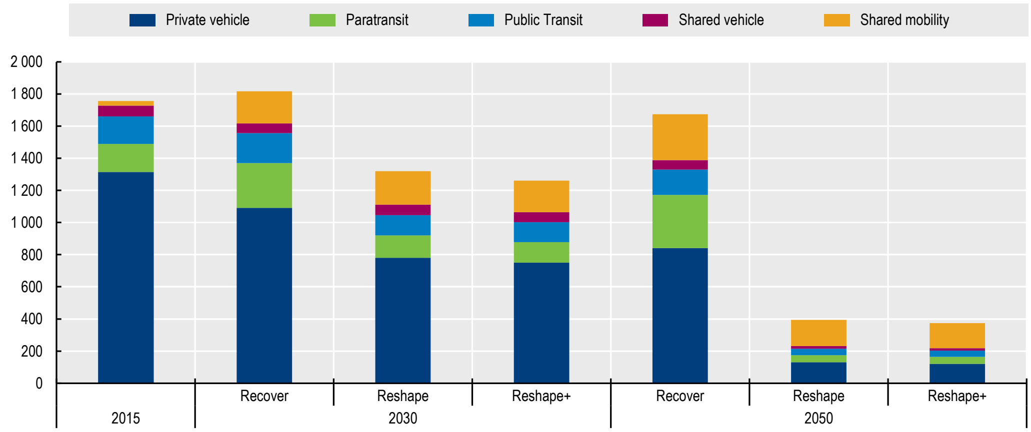


Note: EEA refers to the European Economic Area. LAC refers to Latin America and the Caribbean. MENA refers to the Middle East and North African countries. OECD Pacific countries include Australia, Japan, New Zealand and South Korea. SSA refers to Sub Saharan Africa. Transition economies include countries that were part of the Former Soviet Union and non-EU south-eastern European countries.

Source: ITF modelled estimates

Figure 6. CO_2 emissions from urban passenger transport, by mode

Million tonnes CO_2 direct emissions (tank to wheel)

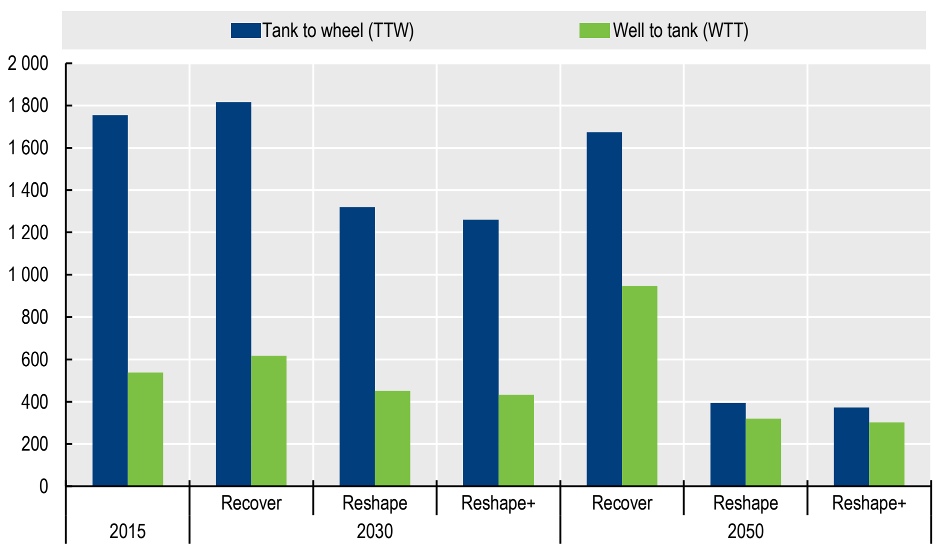


Note: Active and micromobility includes walking, biking, scooter sharing, and bike sharing. Public transport includes PT rail, metro, bus, LRT, and BRT. Paratransit includes informal buses and PT three-wheeler. Shared vehicle includes motorcycle and car sharing. Private Vehicle includes motorcycles and cars. Shared mobility includes taxis, ride sharing, and taxi buses.

Source: ITF modelled estimates

Figure 7. Evolution of tank to wheel vs. well to tank CO_2 emissions from urban passenger transport

Million tonnes CO_2

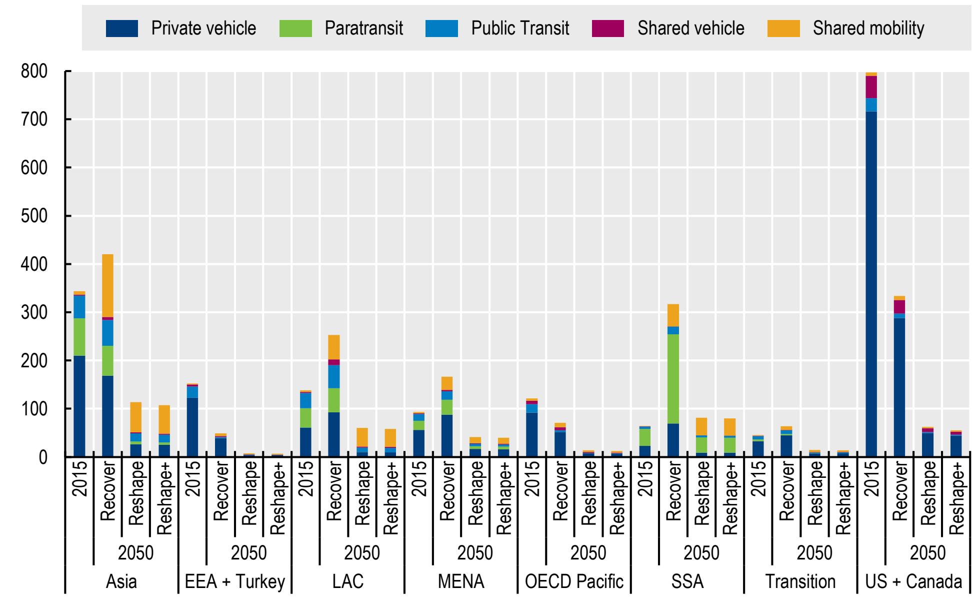


Note: Tank to wheel emissions are emissions produced by using a vehicle (i.e. from the vehicle fuel consumption). Well to tank emissions are created during energy production. For instance, well to tank emissions for electric vehicles includes the emissions produced during electricity production, while tank to wheel emissions are null.

Source: ITF modelled estimates

Figure 8. CO_2 emissions from urban passenger transport, by region

Million tonnes CO_2 direct emissions (tank to wheel)

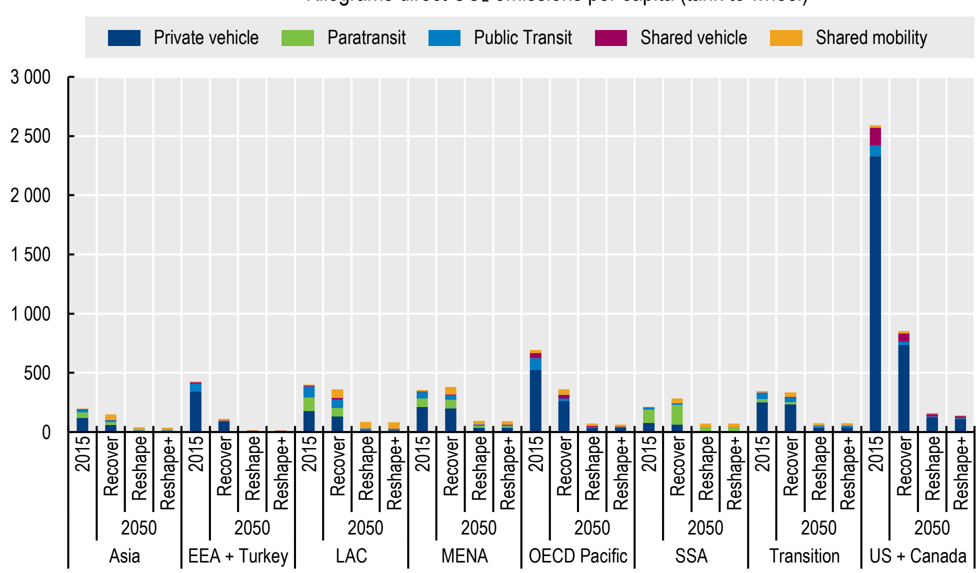


Note: EEA refers to the European Economic Area. LAC refers to Latin America and the Caribbean. MENA refers to the Middle East and North African countries. OECD Pacific countries include Australia, Japan, New Zealand and South Korea. SSA refers to Sub Saharan Africa. Transition economies include countries that were part of the Former Soviet Union and non-EU south-eastern European countries.

Source: ITF modelled estimates

Figure 9. Per capita CO_2 emissions from urban passenger transport, by region

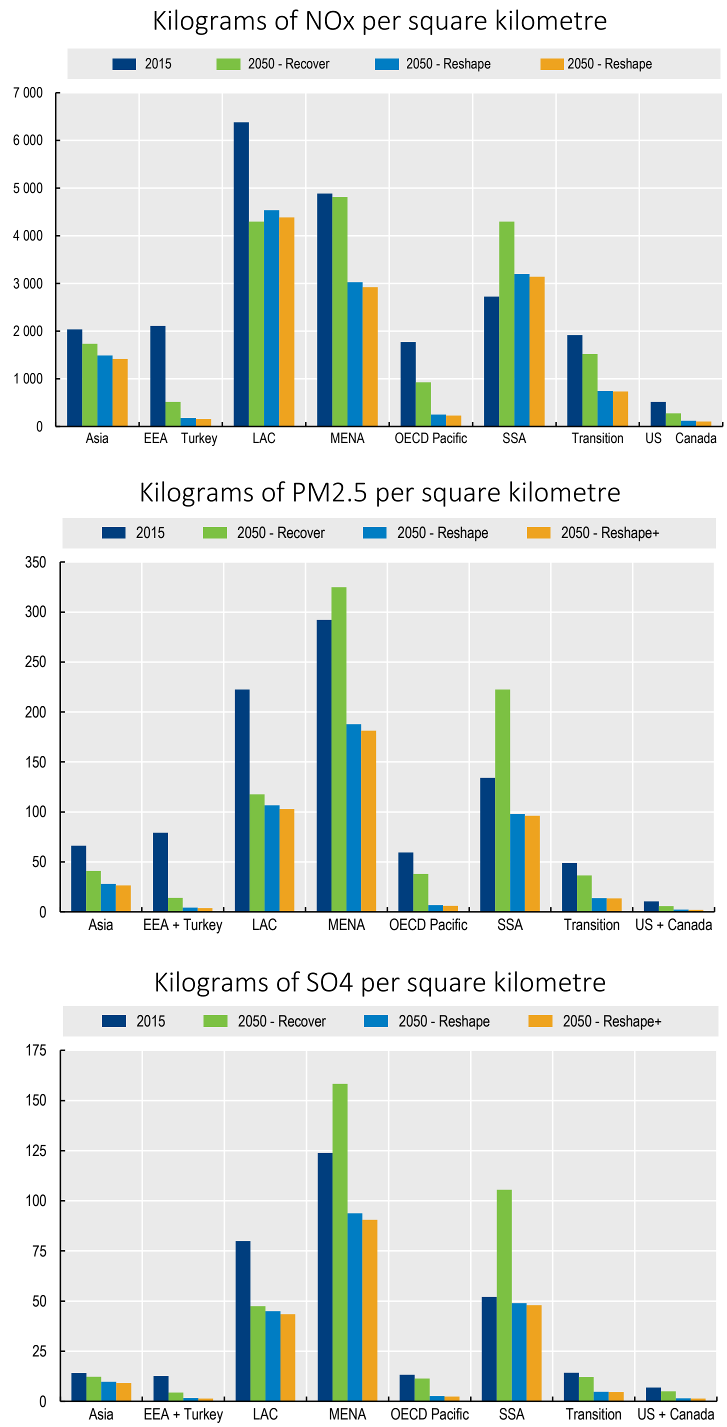
Kilograms direct CO_2 emissions per capita (tank to wheel)



Note: EEA refers to the European Economic Area. LAC refers to Latin America and the Caribbean. MENA refers to the Middle East and North African countries. OECD Pacific countries include Australia, Japan, New Zealand and South Korea. SSA refers to Sub Saharan Africa. Transition economies include countries that were part of the Former Soviet Union and non-EU south-eastern European countries.

Source: ITF modelled estimates

Figure 10. Pollutant emissions from urban passenger transport, by region



Note: EEA refers to the European Economic Area. LAC refers to Latin America and the Caribbean. MENA refers to the Middle East and North African countries. OECD Pacific countries include Australia, Japan, New Zealand and South Korea. SSA refers to Sub Saharan Africa. Transition economies include countries that were part of the Former Soviet Union and non-EU south-eastern European countries

Source: ITF modelled estimates

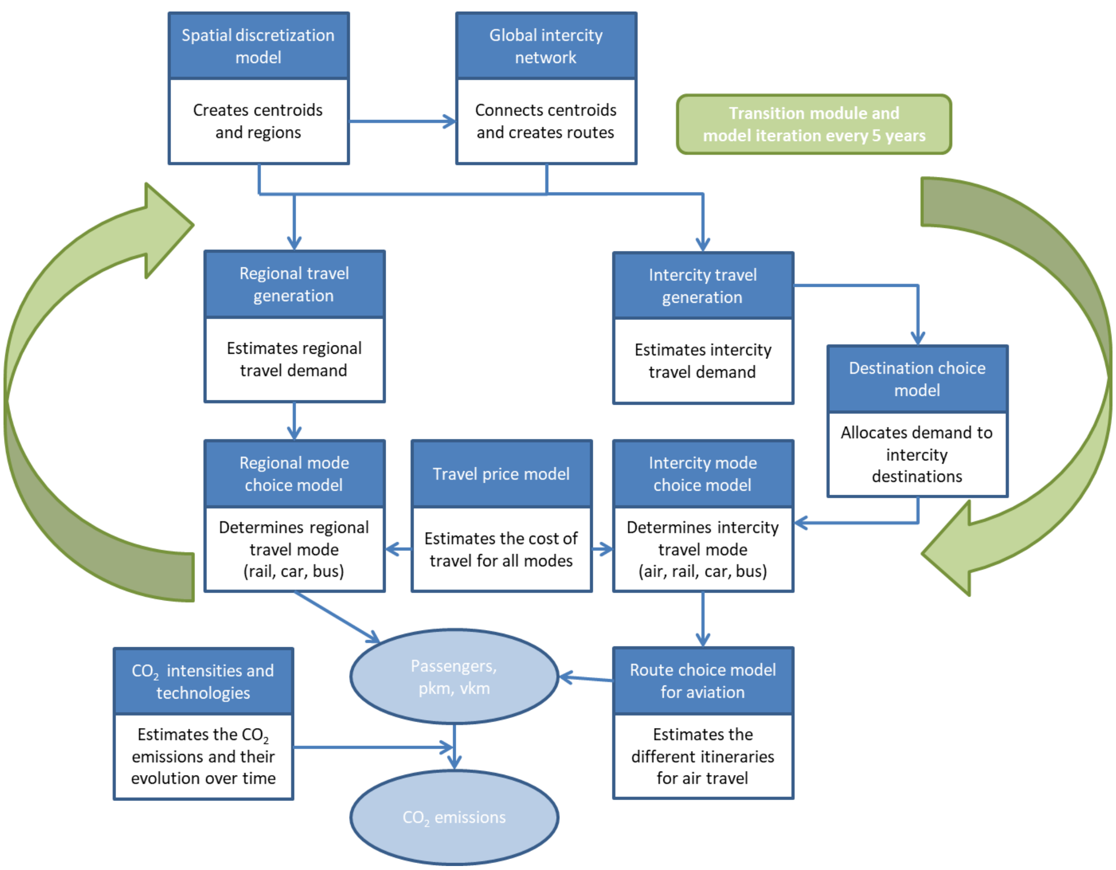
ITF global non-urban passenger model assessment framework

Demand transformative phenomena modelling

The ITF non-urban passenger model is a strategic tool that tests the impacts of multiple policies and trends on the non-urban passenger sector. The model provides scenario forecasts for non-urban transport activity and its related CO2 emissions up to 2050. The model estimates activity between urban areas (intercity travel) and passenger activity happening locally in non-urban areas (intra-regional travel). The latter includes travel in peri-urban and rural areas. The model is developed to assess the impact of transport, economic and environmental policy measures (air liberalisation, carbon pricing, etc.), as well as the impact of technological developments and breakthroughs (electric aviation, autonomous vehicles, etc.).

The model builds on two older ITF models, the international passenger aviation model and the domestic non-urban passenger model. The new non-urban model combines and enhances these two models, now accounting for all multimodal passenger activity that occurs outside of urban areas. The model structure comprises eleven sub-models (or modules) that estimate the non-urban passenger transport activity and its effects on the environment.

Figure 11. Non-urban passenger model scheme



Source: ITF.

A large set of measures has been incorporated in the model to assess the future of non-urban passenger demand in a strong decarbonisation context. These measures were integrated into the model as presented in the following table.

Table 3. Model implementation of policy measures / phenomena for non-urban passenger transport

Measure/Phenomena	Description	Implementation in the model
	Economic instruments	
Ticket taxes (air travel)	Percentage tax applied on the cost of air fare	Increases cost of air travel by implementing a ticket tax, affecting travel propensity and mode choice models.
Carbon pricing	Charges applied on tailpipe CO_2 emissions	Increases cost of all carbon emitting modes affecting travel propensity and mode choice models.
	Enhancement of infrastructure	
Development of ultra-high-speed rail	Introduction of new ultra-high-speed rail routes , such as Maglev	Development of ultra-high-speed-rail infrastructure between cities where it is economically feasible (impacts travel propensity and mode choice model).
Improvements in rail infrastructure	Investments in existing rail infrastructures leading to frequency and speed increases	Increased high-speed rail frequency and quality of service affecting mode choice model.
	Regulatory instruments	
Synthetic fuels (aviation)	Decrease of synthetic aviation fuel cost relative to conventional fuel as a result of technological developments	Increases the cost of air travel and reduces emissions.
Mandates in aviation for sustainable aviation fuels (SAF)	SAF should constitute a minimum percentage of total fuel used	Assess the potential substitution of standard jet-fuel with synthetically generated fuel based on some development and cost assumptions (Cost-benefit analysis).
	Operational instruments	
Optimise aircraft movements	Flights are closer aligned to greater circle paths	Reduces air travel distance allocated for take-off and landing.
	Simulation of innovation and development	
Electric/alternative fuel vehicle penetration	Increased penetration of electric vehicles in non-urban road transport	Increases the uptake of electric vehicles, changing costs and derived activity emissions.
Hybrid-electric planes	Development of new hybrid-electric aircraft.	Assess the potential substitution of standard jet-fuel with partially electric planes, adjusting costs and technological availability for each OD pair (cost-benefit analysis).
Ride sharing/shared mobility	Increased ridership in non-urban road transport (car & bus)	Increases car and bus load factors that affects costs and mode choice model.
Mobility as a Service (MaaS) and multimodal travel services	Improved integration between different transport modes. Integration of ticketing and increase of intermodal terminals/stations	Enables the use of multiple modes in non-urban travel
Improvement in range and cost of all-electric planes	Development of all-electric aircraft	Decreases the cost of electric aviation (cost-benefit analysis assessment for each OD pair)
	Exogenous factors	
Autonomous vehicles	Introduction of vehicles with level 5 autonomous capabilities	Update car and bus costs in modal choice model.
Reduction in long-distance leisure-tourism	Reduced tendency to take long-distance leisure trips as a consequence of Covid-19 pandemic	Exogenous reduction in the propensity to travel for trips longer than 4 hours.
Reduction in business travel due to teleconferencing	Replacement of business trips with teleconferencing as a consequence of Covid-19 pandemic	Exogenous reduction in the propensity to travel for work related trips (around 15% of all intercity travel).
Reduced propensity to fly	Segments of the population avoid flying due to climate considerations	Exogenous reduction in the propensity to fly.

Demand transformative phenomena assumptions in the tested narratives

ITF has implemented the model to the three described narratives / scenarios. Table 4Table 2 presents the details of the scenario specification, the range of implementation across world regions and the calendar of assumptions of measures or phenomena that affect the urban transport demand and derived energy consumption and emissions.

Table 4. Scenario specifications for non-urban passenger transport

Measure/Exogenous Factor	Description	Recover	Reshape	Reshape+
Economic instruments				
Ticket taxes (air travel)	Percentage tax applied on the cost of air fare	Ticket taxes vary across regions: 3% - 15% in 2050	Ticket taxes vary across regions: 8% - 30% in 2050	
Carbon pricing	Charges applied on tailpipe CO_2 emissions	Carbon pricing varies across regions : 150 - 250 USD per tonne of CO_2 in 2050	Carbon pricing varies across regions : 300 - 500 USD per tonne of CO_2 in 2050	
Enhancement of infrastructure				
Development of ultra-high-speed rail	Introduction of new ultra-high-speed rail routes , such as Maglev	No development of new ultra-high-speed rail	Development of Maglev routes where economically feasible	
Improvements in rail infrastructure	Investments in existing rail infrastructures leading to frequency and speed increases	Frequency increases by 50% (year of improvement varies across regions)	Frequency (50%) and speed (20%) improvements across regions	Earlier frequency (50%) and speed (20%) improvements across regions
Regulatory instruments				
Synthetic fuels (aviation)	Decrease of synthetic aviation fuel cost relative to conventional fuel as a result of technological developments	Synthetic fuels cost is 3.3 times more expensive than conventional fuel	Synthetic fuels cost is 3 times more expensive than conventional fuel	
Mandates in aviation for sustainable aviation fuels (SAF)	SAF should constitute a minimum percentage of total fuel used	Minimum SAF percentage varies across regions 5% - 10% in 2050	Minimum SAF percentage varies across regions 10% - 25% in 2050	Minimum SAF percentage varies across regions 15% - 30% in 2050
Operational instruments				
Optimise aircraft movements	Flights are closer aligned to greater circle paths	Deviations are reduced by 50% in 2030	Deviations are reduced by 50% in 2020	
Simulation of innovation and development				
Electric/alternative fuel vehicle penetration	Increased penetration of electric vehicles in non-urban road transport	Follows the IEA NPS Scenario	Follows the IEA SDS Scenario	Increased penetration on top of IEAs SDS Scenario
Hybrid-electric planes	Development of new hybrid-electric aircraft.	Hybrid-electric aircraft are available from the year 2030. They provide 5% - 7.5% of total energy required reaching up to 20% - 30% in 2050 depending on the region.	Hybrid-electric aircraft are available from the year 2030. They provide 7.5% - 10% of total energy required reaching up to 30% - 40% in 2050 depending on the region.	
Ride sharing/shared mobility	Increased ridership in non-urban road transport (car & bus)	The percentage of shared trips of total trips by car equals 6.7%	The percentage of shared trips of total trips by car, varies across regions 13.3% – 20.0%	

Mobility as a Service (MaaS) and multimodal travel services	Improved integration between different transport modes. Integration of ticketing and increase of intermodal terminals/stations	Switching between different modes is twice as penalizing than between the same mode	Switching between different mode is no more penalizing than between the same mode	
Improvement in range and cost of all-electric planes	Development of all-electric aircraft	Flying range of all-electric planes increases by 2050 up to 1 000 km Cost of all-electric aviation is 1.5 times that of conventional aircraft	Flying range of all-electric planes increases by 2050 up to 1 500 km Cost of all-electric aviation is 1.2 times that of conventional aircraft	
Exogenous factors				
Autonomous vehicles	Introduction of vehicles with level 5 autonomous capabilities The percentage of autonomous vehicles in use varies across regions: for car 0% - 2.5%, for bus 0% - 1.25%			
Reduction in long-distance leisure-tourism	Reduced tendency to take long-distance leisure trips as a consequence of Covid-19 pandemic	none	none	Long distance trips are reduced by 15% - 22% in 2030, reaching 0% in 2050.
Reduction in business travel due to teleconferencing	Replacement of business trips with teleconferencing as a consequence of Covid-19 pandemic	none	none	Air trips are reduced by 12.5% in 2030, reaching a 2.5% reduction in 2050.
Reduced propensity to fly	Segments of the population avoid flying due to climate considerations	10% - 15% fewer people fly in some regions in 2050	5% - 30% fewer people fly in most regions in 2050	

Note: Range of values reflect the varying degrees of implementation of policy measures across the different world regions in each scenario.

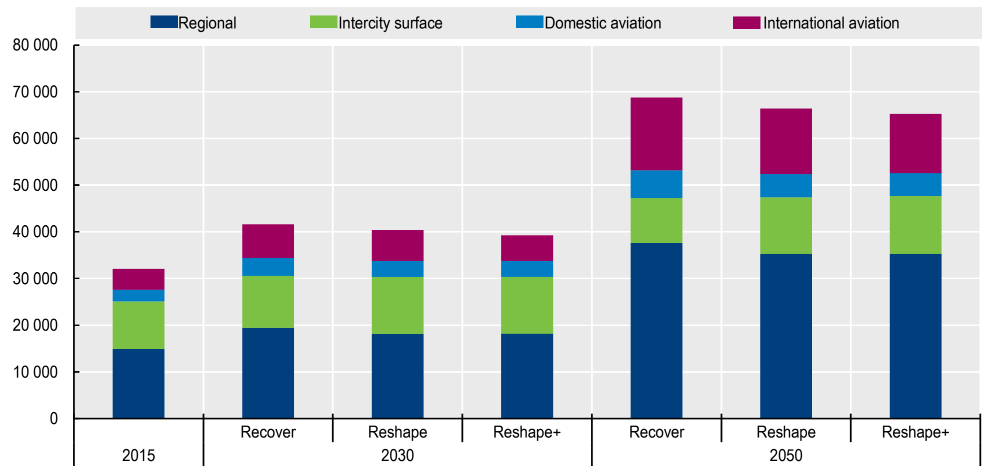
Autonomous vehicles are considered but are not a primary factor in any of the scenarios. All scenarios assume a constant level of introduction of vehicles with Level 5 autonomy. The *ITF Transport Outlook 2019* focussed more specifically on transport disruptions, including autonomous vehicles, and assessed related scenarios

Main results for the tested scenarios

The narratives and scenarios designed by ITF for the ITF 2021 Outlook lead to three different future outcomes. The next figures and tables describe some of them. A detail analysis at country level can be performed in the detailed dataset provided in annex to this report.

Figure 12. Demand for non-urban passenger transport, by sub-sector

Billion passenger-kilometres

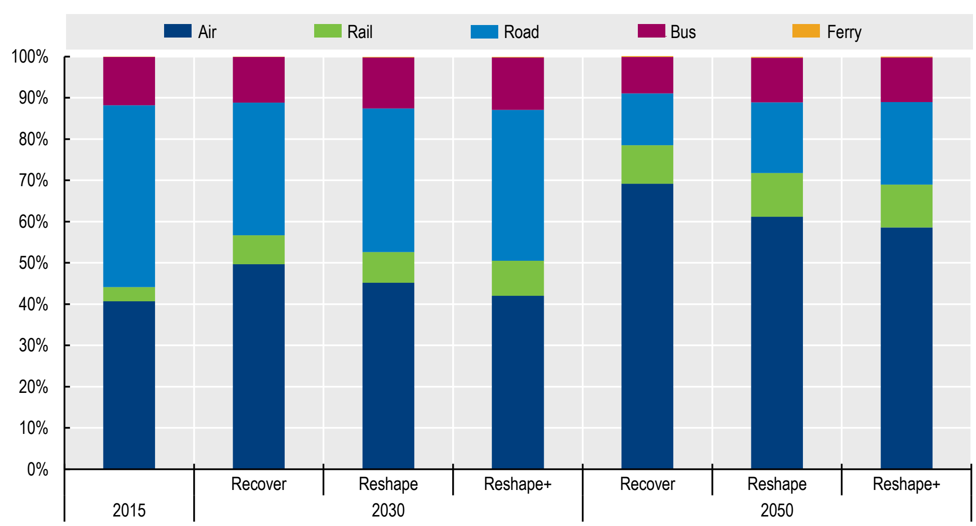


Note: Regional refers to local transport activity happening outside urban areas; intercity surface refers to transport movements by private road vehicles, buses, and rail between urban areas

Source: ITF modelled estimates

Figure 13. Average non-urban passenger mode shares

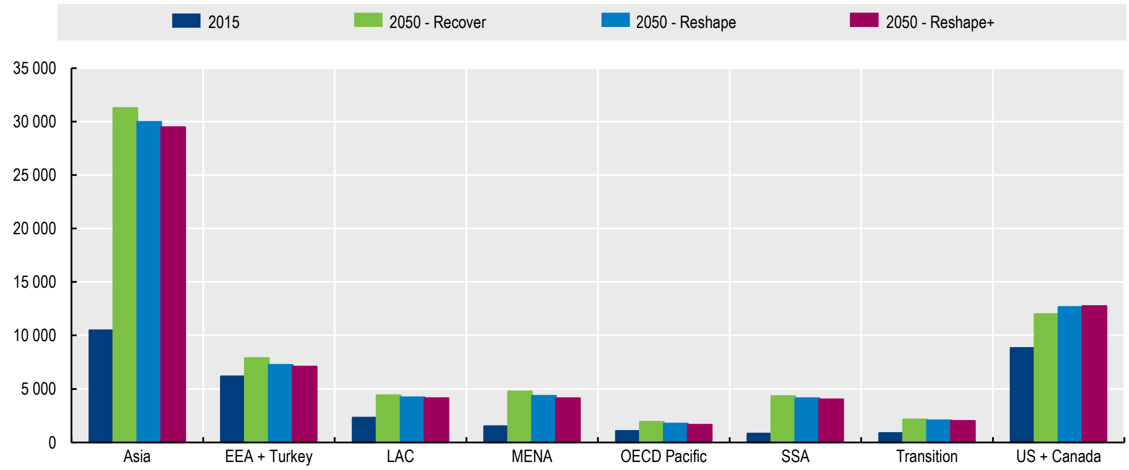
Mode share in passenger-kilometres



Source: ITF modelled estimates

Figure 14. Demand for non-urban passenger transport, by region

Billion passenger-kilometres

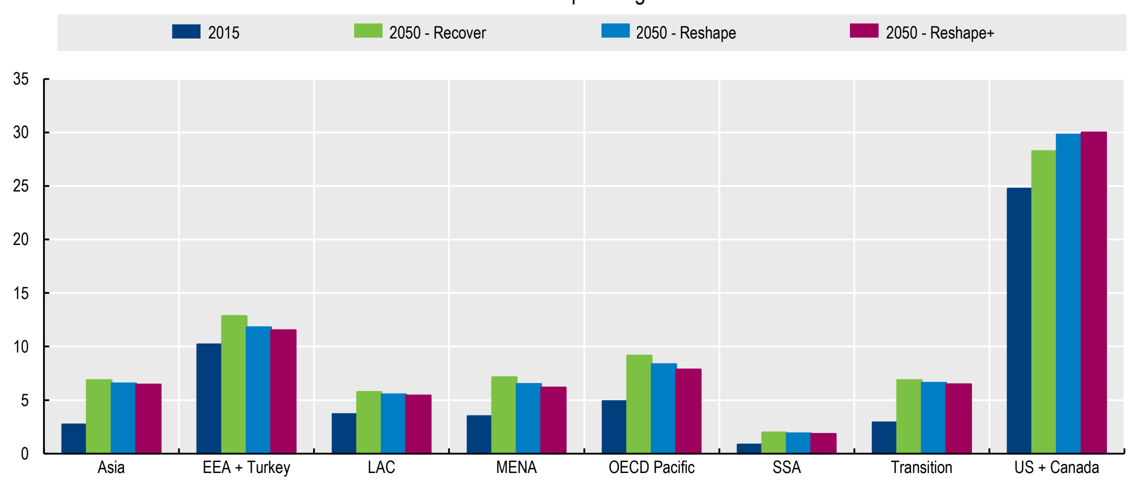


Note: EEA refers to the European Economic Area. LAC refers to Latin America and the Caribbean. MENA refers to the Middle East and North African countries. OECD Pacific countries include Australia, Japan, New Zealand and South Korea. SSA refers to Sub Saharan Africa. Transition economies include countries that were part of the Former Soviet Union and non-EU south-eastern European countries.

Source: ITF

Figure 15. Per capita demand for non-urban passenger transport, by region

Thousand passenger-kilometres

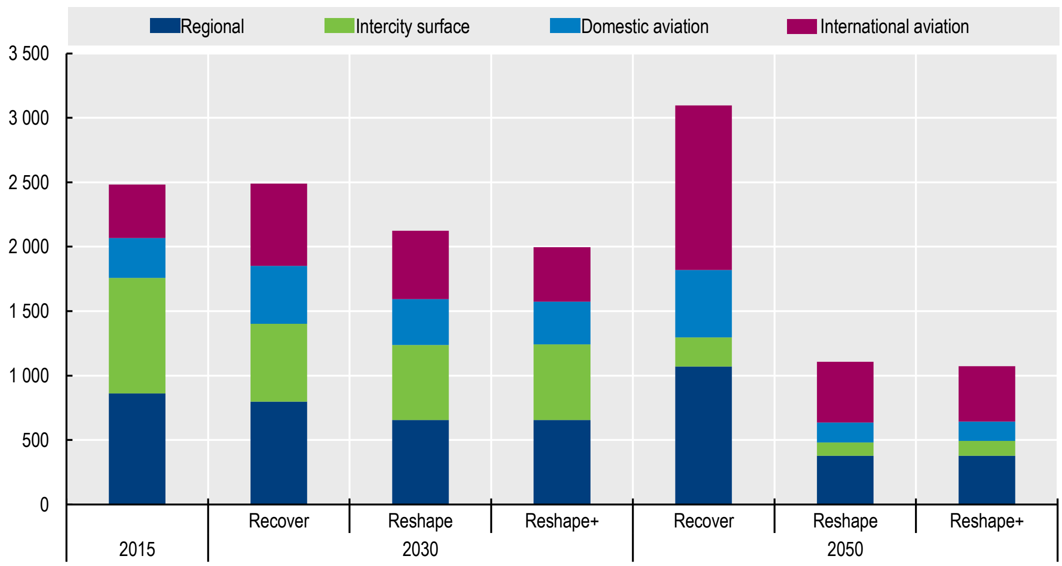


Note: EEA refers to the European Economic Area. LAC refers to Latin America and the Caribbean. MENA refers to the Middle East and North African countries. OECD Pacific countries include Australia, Japan, New Zealand and South Korea. SSA refers to Sub Saharan Africa. Transition economies include countries that were part of the Former Soviet Union and non-EU south-eastern European countries.

Source: ITF modelled estimates

Figure 16. CO_2 emissions from urban passenger transport, by mode

Million tonnes CO_2 emissions (tank to wheel/wake)

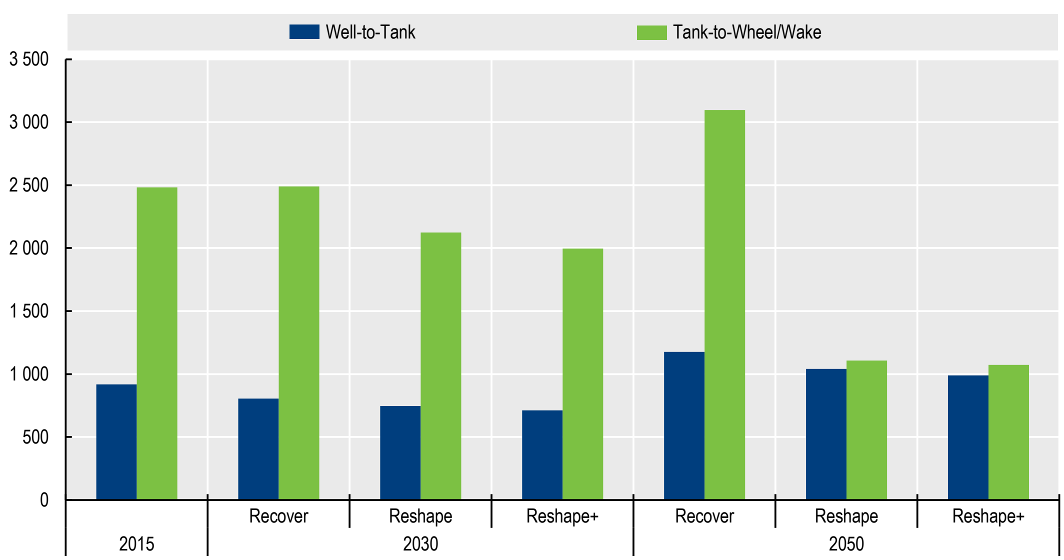


Note: Regional refers to local transport activity happening outside urban areas; intercity surface refers to transport movements by private road vehicles, buses, and rail between urban areas

Source: ITF modelled estimates

Figure 17. Evolution of tank-to-wheel vs. well-to-tank CO_2 emissions from non-urban passenger transport

Million tonnes CO_2

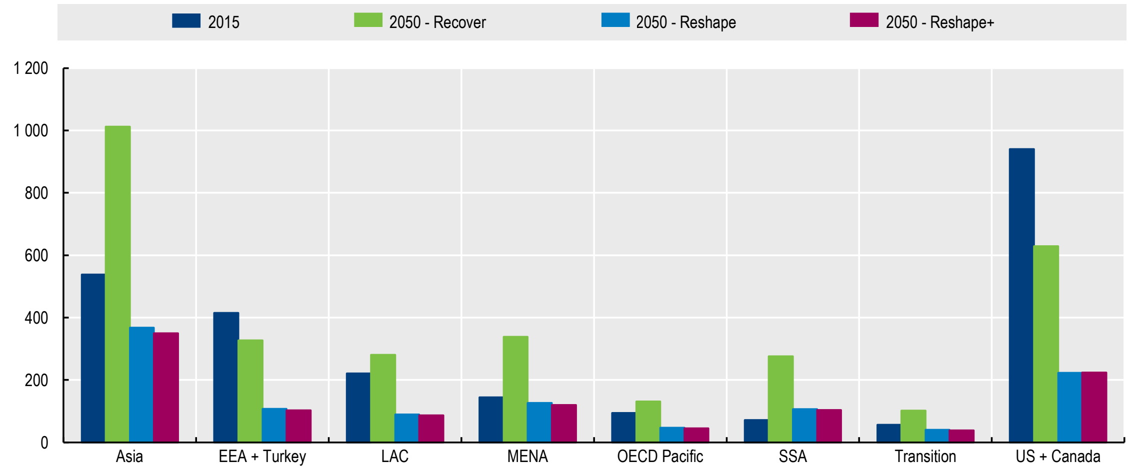


,

Source: ITF modelled estimates

Figure 18. CO_2 emissions from non-urban passenger transport, by region

Million tonnes CO_2 emissions (tank to wheel/wake)

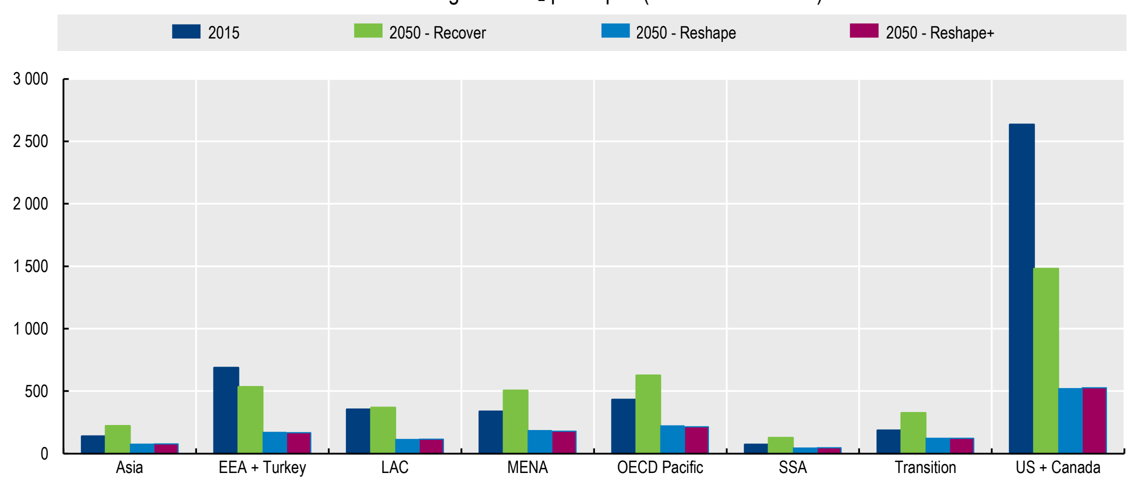


Note: EEA refers to the European Economic Area. LAC refers to Latin America and the Caribbean. MENA refers to the Middle East and North African countries. OECD Pacific countries include Australia, Japan, New Zealand and South Korea. SSA refers to Sub Saharan Africa. Transition economies include countries that were part of the Former Soviet Union and non-EU south-eastern European countries.

Source: ITF modelled estimates

Figure 19. Per capita CO_2 emissions for non-urban passenger transport, by region

Kilograms CO_2 per capita (tank to wheel/wake)



Note: EEA refers to the European Economic Area. LAC refers to Latin America and the Caribbean. MENA refers to the Middle East and North African countries. OECD Pacific countries include Australia, Japan, New Zealand and South Korea. SSA refers to Sub Saharan Africa. Transition economies include countries that were part of the Former Soviet Union and non-EU south-eastern European countries.

Source: ITF modelled estimates

ITF global freight model assessment framework

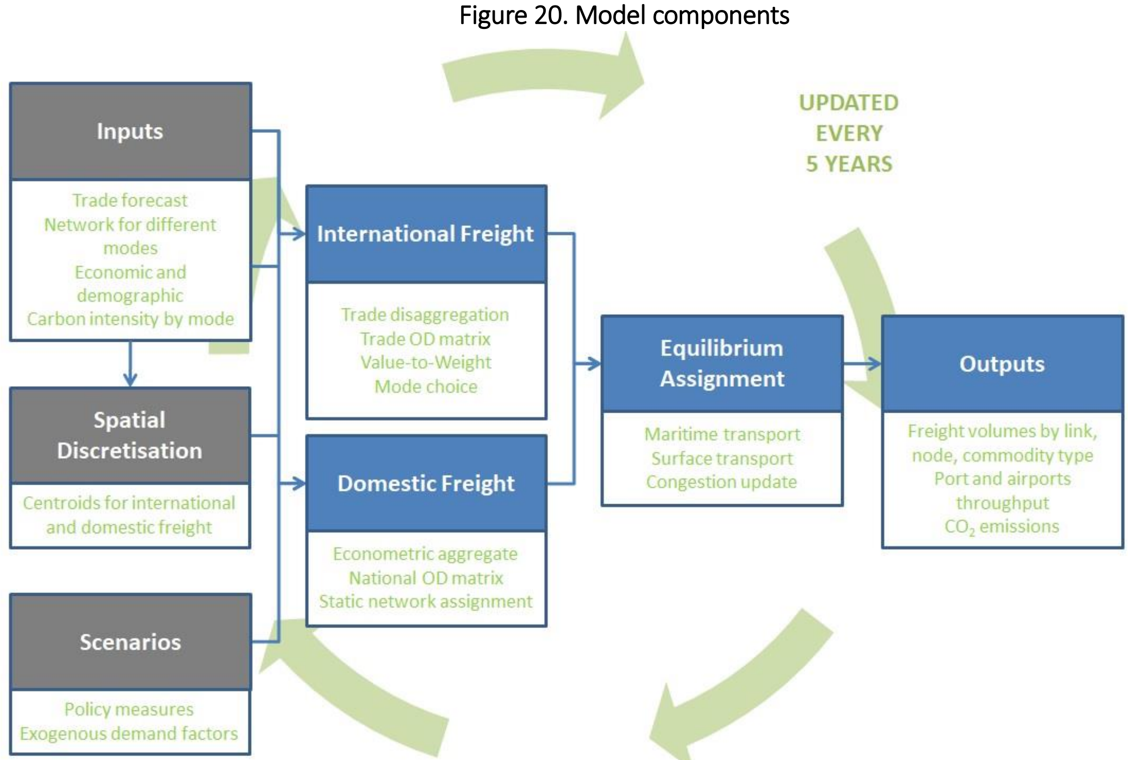
Demand transformative phenomena modelling

The ITF non-urban freight transport model assesses and provides scenario forecasts for freight flows around the globe. It is a network model that assigns freight flows of all major transport modes to specific routes, modes, and network links. Centroids, connected by network links, represent zones (countries or their administrative units) where goods are consumed or produced.

The most recent version of the ITF freight model integrates the (previously distinct) surface and international freight models. International and domestic freight flows are calibrated on data on national freight transport activity (in tonnes-kilometres, tkm) as reported by ITF member countries. Reported data is also used to validate the route assignment of freight flows. Trade projections in value terms stem from the OECD trade model and converted into cargo weight (tonnes). These weight movements are then assigned to an intermodal freight network that develops over time in line with scenario settings. These define infrastructure availability, available services and related costs.

The current version of the model estimates freight transport activity for 19 commodities for all major transport modes including sea, road, rail, air and inland waterways. The underlying network contains more than 8 000 centroids, where consumption and production of goods takes place. Each of the more than 150 000 links of the network is described by several attributes. These include length, capacity, travel time (incl. border crossing times), and travel costs (per tkm).

Figure 20. Model components



Source: ITF

A large set of measures has been incorporated into the model to assess the future of non-urban passenger demand in a strong decarbonisation context. These measures were integrated into the model as presented in the following table.

Table 5. Model implementation of policy measures / phenomena for freight transport

Measure/Phenomena	Description	Implementation in the model
	Economic Instruments	
Distance charges	Charges introduced to road haulage.	Road costs would update costs based on verified congestion at each road link. Impacts mode choice and route choice.
Port fees	Port fees that promote cleaner vessels uptake.	This element only impact the CO2 intensity of the affected modes and the conversion of vkms to CO2 emissions.
Carbon pricing	Carbon pricing across all modes.	Adapt the cost of each mode to reflect the CO2 cost per km. Impacts mode choice and route choice.
	Enhancement of infrastructure	
Rail and inland waterways improvements	Improvement of the rail and waterways performance.	Changes in the speed and resulting operational costs. These changes reflect in mode choice model.
Transport network improvement plans	Integration of plans of infrastructure development worldwide.	Creation of new links (mainly rail) that increase efficiency and change costs in the model choice model.
Energy transition for long-haul heavy-duty road freight vehicles	Development of solutions to decarbonisation of long distance road haulage (e.g. electric highways, hydrogen trucks).	Update costs and the resulting CO_2 emission per vkm for road. This affects the value-weight conversion and the modal choice model.
	Operations management	
Asset sharing and the Physical Internet	Increase of road freight load factors by sharing available space at vehicles amongst different hauliers.	The adoption of shared assets allows the increase of load factors in road based modes. This impacts mode choice and the conversion of tkms to vkms.
	Regulatory instruments	
Slow steaming and speed reduction for maritime and trucks	Adapt the speed of vessel to reduce their energy consumption.	Reduce the sea CO_2 intensities per ton/km by reducing energy consumption at lower speeds. This impacts mode choice and route choice.
Fuel economy standards for internal combustion engine (ICE) vehicles and fuel	Set and improve fuel economy standards for internal combustion engine (ICE) vehicles and fuel.	Reduce carbon intensity of road freight, updating cost and the derived utilities in the mode choice model.
Low emission fuel incentives (including electric vehicles) and investment in distribution/supply infrastructure	Development of incentives to low carbon fuels and infrastructure.	Reduce carbon intensity of road freight, updating cost and the derived utilities in the mode choice model.
Heavy Capacity Vehicles (HCV)	Increase the share of high capacity vehicles in and there size in the road long haulage fleet.	Update costs and the resulting CO_2 emission per pkm for road. This affects the value-weight conversion and the modal choice model.
	Stimulation of innovation and development	
Autonomous Vehicles and Platooning	Implementation of platooning measures and autonomous trucks within highways.	Adaptation of road freight cost and fuel efficiency, affecting the modal choice model.

Electric/alternative fuel vehicle penetration	Increased penetration of electric vehicles in freight transport	Increases the uptake of electric vehicles, changing costs and derived activity emissions.
Intelligent Transport Systems (ITS) and eco-driving	Increase of ITS and eco-driving practices within the road haulage fleets.	Update the CO_2 emission per pkm for road. This affects the modal choice model.
Exogenous factors		
3D Printing	3D printing uptake in several freight commodities	Change in the trade volumes of the different commodities. The model leads to an increase of raw materials transport and reduction in some manufactured good.
Decarbonisation of energy	Adapt international trade to the new energy scenario compatible with decarbonisation	Reduce the volume traded from carbon based energy source and increase of some minerals that are key for battery production
Trade regionalisation	Implementation of measures that incentivise regional trade and near shoring.	Varies intra and inter regional transport costs to lead to slight global trade variations between export and imports.
E-commerce	Adapt world trade forecast to a greater increase of global e-commerce.	Increase of trade volumes of wholesale trade and manufactured goods values.

Demand transformative phenomena for assumptions in the tested narratives

ITF has implemented the model to the three described narratives / scenarios. Table 6 present the details of the scenario specification, the range of implementation across world regions and the calendar of assumptions of measures or phenomena that affect the urban transport demand and derived energy consumption and emissions.

Table 6. Scenario specifications for freight transport

Measure	Recover	Reshape	Reshape+
Economic Instruments			
Distance charges	Charges introduced in 2030 growing to 1 cent per tonne-kilometre by 2050.	Charges introduced in 2030 growing to 2.5 cent per tonne-kilometre by 2050.	Charges introduced in 2025 growing to 6 cent per tonne-kilometre by 2050.
Port fees	Port fees grow an additional 1% by 2050 decreasing carbon intensity of shipping by 0.5%.	Port fees grow an additional 20% by 2050 decreasing carbon intensity of shipping by 10%.	Port fees grow an additional 30% by 2050 decreasing carbon intensity of shipping by 15%.
Carbon pricing	Carbon pricing varies across regions: 150 - 250 USD per tonne of CO2 in 2050.	Carbon pricing varies across regions: 300 - 500 USD per tonne of CO2 in 2050.	Carbon pricing varies across regions: 300 to 500 USD per tonne of CO2 in 2050.
Enhancement of infrastructure			
Rail and inland waterways improvements	The penalty for mode transfers at intermodal terminals is decreased and alternative specific constant of rail and inland waterways increases. The rate of change varies by world region, e.g. in Western Europe it grows from 2% in 2020 to 20% in 2050.	The penalty for mode transfers at intermodal terminals is decreased and alternative specific constant of rail and inland waterways increases. The rate of change varies by world region, e.g. in Western Europe it grows from 4% in 2020 to 40% in 2050.	The penalty for mode transfers at intermodal terminals is decreased and alternative specific constant of rail and inland waterways increases. The rate of change varies by world region, e.g. in Western Europe it grows from 10% in 2020 to 80% in 2050.

Transport network improvement plans	The transport network is updated with planned new infrastructure and upgrades (e.g. increases in port capacity, developments in Central Asia, TEN-T European projects) expected to become operational between 2020 and 2050.		
Energy transition for long-haul heavy-duty road freight vehicles	Very low, marginal implementation	14% of heavy trucks tkm are on these systems by 2050. Costs begin higher than conventional fuels but by 2050 become lower. Differences in uptakes and costs by regions.	37% of heavy trucks tkm are on these systems by 2050. Costs begin higher than conventional fuels but by 2050 become lower. Differences in uptakes and costs by regions.
Operations management			
Asset sharing and the Physical Internet	Less than 1% Increase in average loads of road freight by 2020 growing to 2% in 2050.	4% Increase in average loads of road freight by 2020 growing to 10% in 2050.	Less than 4% Increase in average loads of road freight in 2020 growing to 20% in 2050. Accelerated increase between 2020 and 2030.
Regulatory instruments			
Slow steaming and speed reduction for maritime and trucks	Decrease in speed of road and maritime transport is less than 1% in 2020, growing to a 10% decrease by 2050.	Decrease in speed of road and maritime transport is 1% in 2020, growing to a 20% decrease by 2050.	Decrease in speed of Road and Maritime modes by more than 1% in 2020, growing to a 33% decrease by 2050.
Fuel economy standards for internal combustion engine (ICE) vehicles and fuel	Carbon intensity per tkm of ICE trucks reduces by less than 1% in 2020 up to 10% by 2020.		Carbon intensity per tkm of ICE trucks reduces by 2% in 2020 up to 15% by 2020.
Low emission fuel incentives (including electric vehicles) and investment in distribution/supply infrastructure	Increases in low emission fuels vehicle shares vary by world-region, in faster adoption regions (e.g. Western Europe) there is an increase of 1% by 2025, growing to 10% by 2050.	Increases in low emission fuels vehicle shares vary by world-region, in faster adoption regions (e.g. Western Europe) there is an increase of 2.6% by 2025, growing to 20% by 2050.	Increases in low emission fuels vehicle shares vary by world-region, in faster adoption regions (e.g. Western Europe) there is an increase of 4% by 2025, growing to 30% by 2050.
Heavy Capacity Vehicles (HCV)	By 2050 2% of non-urban road freight transport activity (tkm) is done with high capacity vehicles.	By 2050 5% of non-urban road freight transport activity (tkm) is done with high capacity vehicles.	By 2050 10% of non-urban road freight transport activity (tkm) is done with high capacity vehicles.
Stimulation of innovation and development			
Autonomous Vehicles and Platooning	Adoption varies by sector (urban and non-Urban) and world-region. Very low to marginal adoption in this scenario.	Up to 45% uptake on non-urban in some regions by 2050 (Europe, North America, China, Japan and South Korea). Uptake on urban freight is lower. Decrease of 14% on carbon intensity and 45% on costs.	Up to 90% uptake on non-urban in some regions by 2050 (Europe, North America, China, Japan and South Korea). Uptake on urban freight is lower. Decrease of 14% on carbon intensity and 45% on costs.
Electric/alternative fuel vehicle penetration	Follows the IEA NPS Scenario.	Follows the IEA SDS Scenario.	
Intelligent Transport Systems (ITS) and eco-driving	Implemented with regional variations, in regions with faster deployment (e.g. Western Europe) reductions of 4% in carbon intensity in 2020 and close to zero in 2050.	Implemented with regional variations, in regions with faster deployment (e.g. Western Europe) reductions of 10% in carbon intensity in 2020 and 1% in 2050.	Implemented with regional variations, in regions with faster deployment (e.g. Western Europe) reductions of 15% in carbon intensity in 2020 and close to 2% in 2050.
Exogenous factors			
3D Printing	Negligible impact on trade.	International trade shrinks 10% by 2050. Values differ by commodities, electronic and manufactured goods have higher falls.	
Decarbonisation of energy	Oil and Coal grow less than other commodities (following	Yearly decrease of 3.35% for coal and 2.1% for oil. By 2050	Yearly decrease of 10% for coal and 2.1% for oil. By 2050

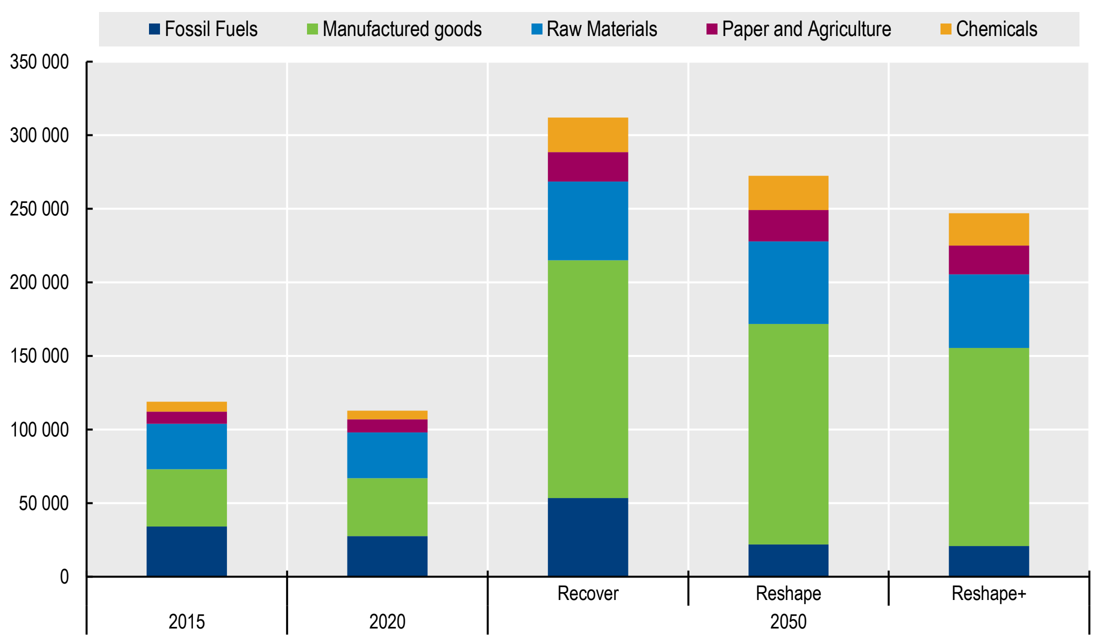
	ENV-Linkages model (ENV-OECD), (Chateau et al., 2014)	coal trade has reduced 65% and oil close to 50%, compared to 2020 estimates.	coal trade has reduced by 96% being almost phased-out globally and there is close to a 50% decrease in oil consumption compared to 2020 estimates.
Trade regionalisation		No additional fees compared to baseline.	5% increase in penalty fees for intra-regional trade.
E-commerce	Urban freight with additional 5% demand increase by 2050, smaller impacts on non-urban freight.		

Main results for the tested scenarios

The narratives and scenarios designed by ITF for the ITF 2021 Outlook lead to three different future outcomes. The next figures and tables describe some of them. A detail analysis at country level can be performed in the detailed dataset provided in annex to this report.

Figure 21. Import related transport activity

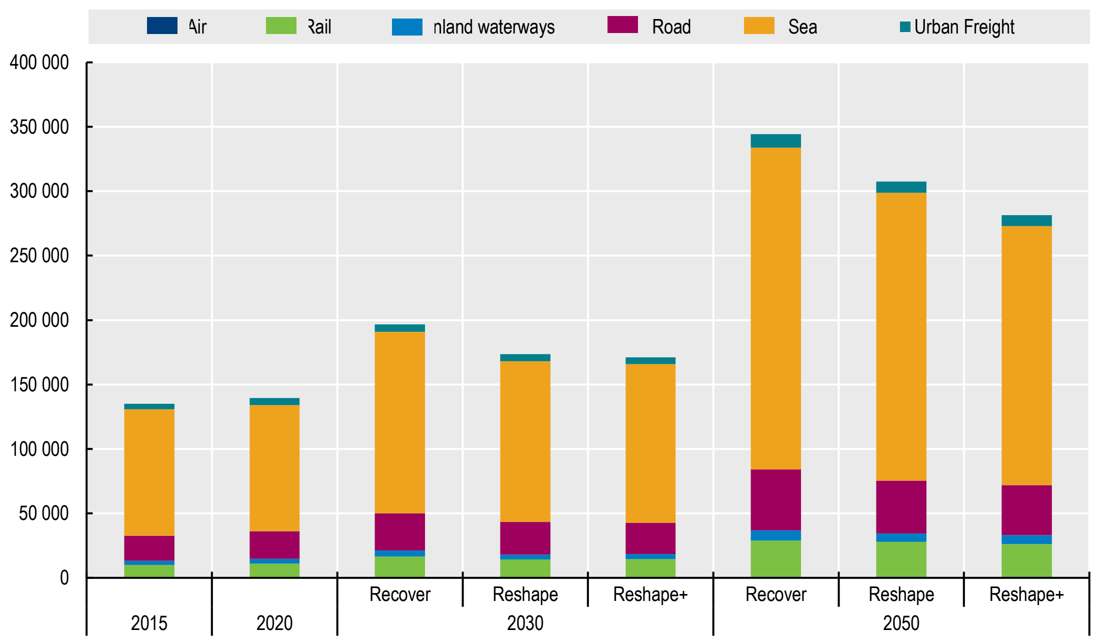
Billion tonne-kilometres



Source: ITF modelled estimates

Figure 22. Projected Freight transport activity by mode

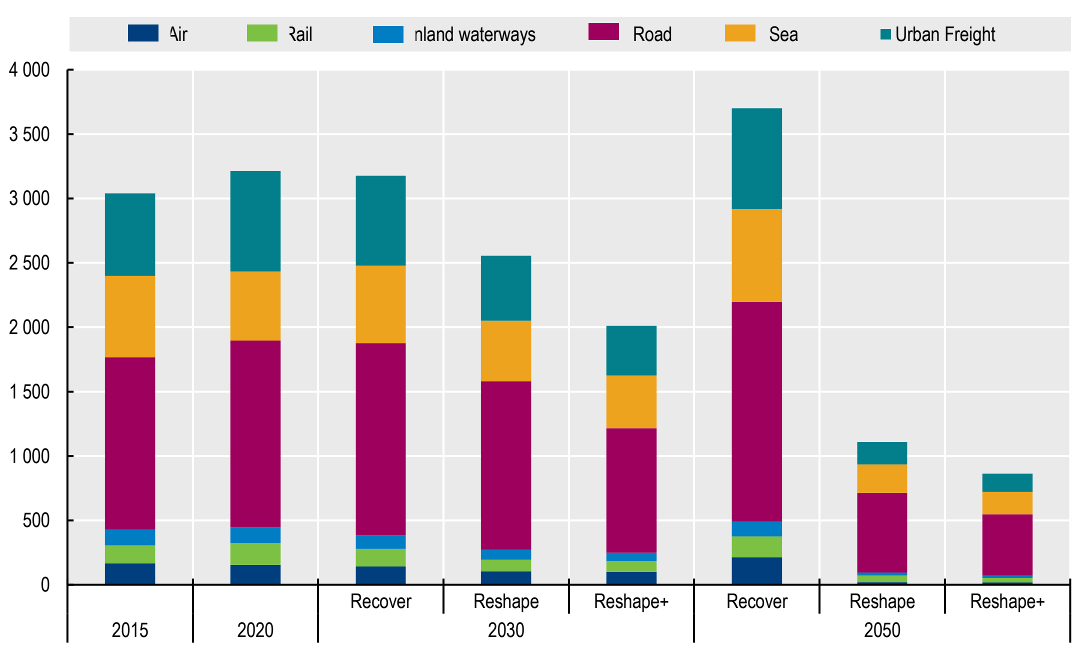
Billion tonnes-kilometres



Source: ITF modelled estimates

Figure 23. Freight transport emissions by mode

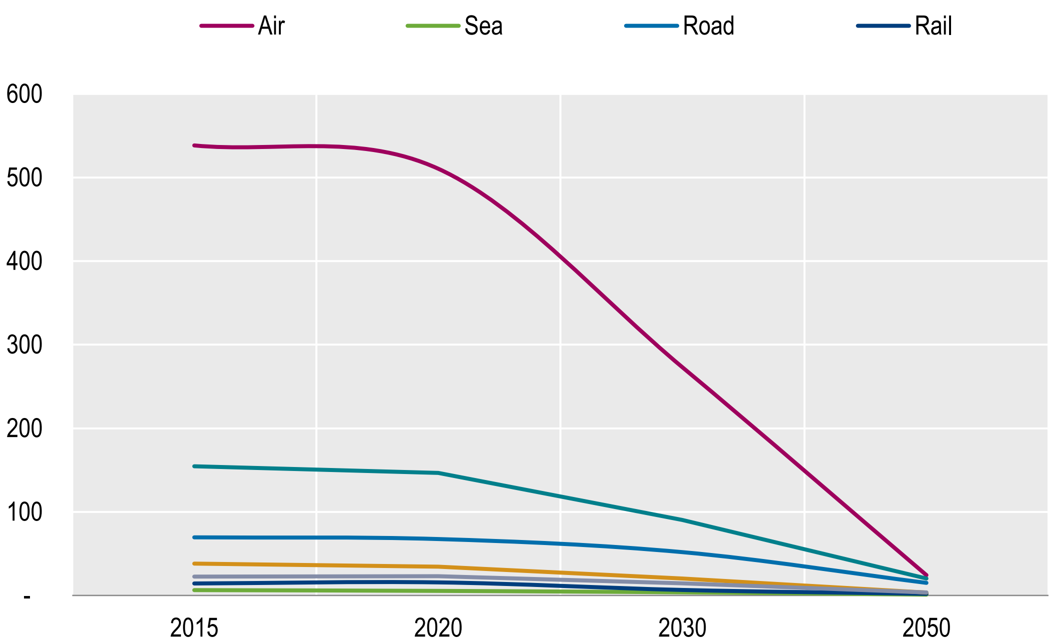
Million tonnes of CO_2



Source: ITF modelled estimates

Figure 24. Carbon intensity of freight transport activity by mode

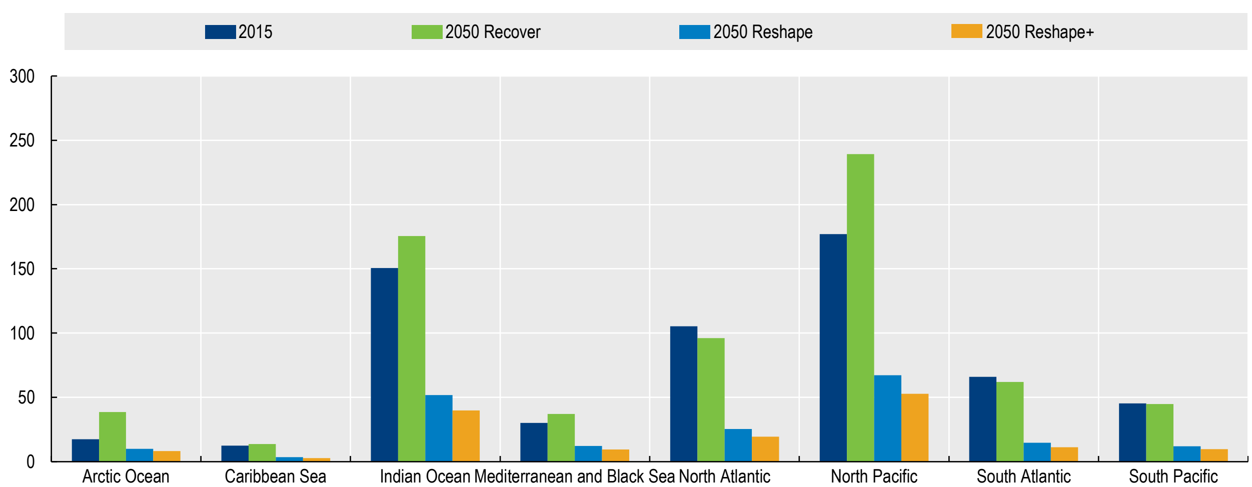
Reshape scenario, grams of CO_2 per tonnes-kilometre



Source: ITF modelled estimates

Figure 25. Surface freight emissions by region

Million tonnes CO_2

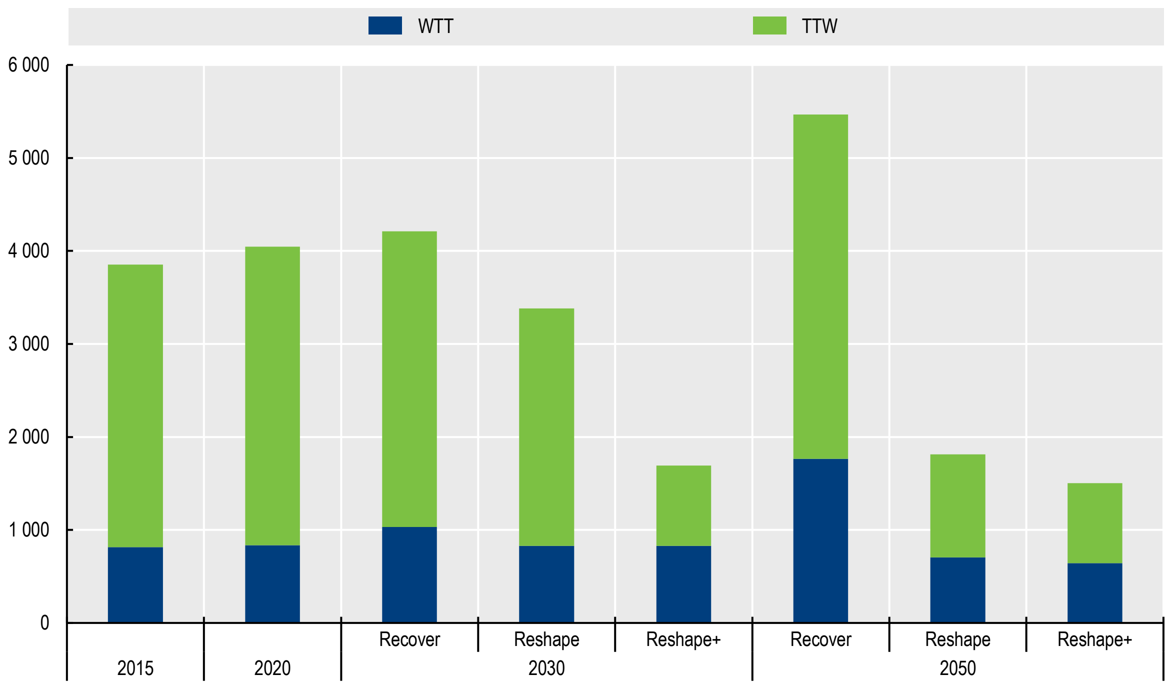


Note: EEA refers to the European Economic Area. LAC refers to Latin America and the Caribbean. MENA refers to the Middle East and North African countries. OECD Pacific countries include Australia, Japan, New Zealand and South Korea. SSA refers to Sub Saharan Africa. Transition economies include countries that were part of the Former Soviet Union and non-EU south-eastern European countries.

Source: ITF modelled estimates

Figure 26. Tank-to-wheel (TTW) and Well-to-tank (WTT) freight transport emissions

Million tonnes CO_2



Source: ITF modelled estimates

Assessment of a demand disruptive phenomena: Shared mobility.

How to incorporate simulation based results and data in aggregate models

The project has received funding from the Research Institute of Innovative Technology for the Earth (RITE) under subcontract agreement D06710.

Assess the impact of massive shared mobility adoption

Abstract

This paper explores the role of massive shared mobility adoption in shaping urban mobility and mitigate CO_2 emissions in different urban contexts and sociodemographic settings. The study examines the implementation of the ITF Shared Mobility simulation framework for assessing the demand and supply behaviour in different cities around the world under different policies that may restrict either car usage or integrate shared mobility with public transport. The same methodological approach was undertaken in five cities around the world: Auckland, New Zealand, Dublin, Ireland, Helsinki, Finland, Lyon, France and Lisbon. The results provide insights about shared mobility adoption and implementation pathway and allowed the calibration of an aggregate model to estimate the potential impact of shared mobility adoption in any urban context around the world.

Keywords

Urban mobility; shared mobility; agent-based modelling; CO_2 mitigation evaluation.

Introduction

A wide range of technological disruptions have been observed in transportation in recent decades. Penetration of shared economy, in which people exchange goods and services, is one of the most remarkable disruptions with a potential to change drastically the conventional transportation systems. Together with ubiquitous digitalisation, which allows the efficient matching of demand and supply, this gives rise to the on-demand shared transport paradigm, especially in urban areas. The emergence of shared mobility services, such as Uber, Lyft, Car2Go and Zipcar, creating new business models by using shared resources in mobility provision changed drastically the landscape of current and potentially cities in the future.

The range of solutions popping up in the market explore a wide spectrum of services. Carsharing options can be provided by a vehicle fleet manager in a round trip basis (pick-up and drop-off vehicle at the same location or station) or a one-way station based or free float where customers may pick or drop-off vehicles either at stations or the street (Car2Go) or a private car short term rental managed through an app-based platform. In terms of ridesharing services, they can be provided ether by transportation network companies (TNC) as Cabify, Uber, Lyft and Taxify as single rider or by sharing the vehicle with small detours as UBERPOOL or Lyft Line in a door-to-door like system, or a public transport operator or shuttle services operator providing dial-and-ride bus with flexible route (street corner-to-street corner) and short term booking service (e.g., Kutsuplus, in Finland, and BRIDJ in the United States of America). or a peer-to-peer ridesharing services either by proving services with your private car using standard app-based platforms as Uber or Lyft. Additionally, sharing a ride can also be considered as standard carpooling organised through an app as BlaBlaCar. These services are already in the market and explore current technologies to expand the spectrum of mobility services at lower costs mainly where public transport is either not sufficiently convenient or the accessibility is quite low. The integration of these services with standard public transport is starting also to be explored as a complementarity solution where shared mobility can feed high capacity and efficient public transport corridors at lower costs and at higher client performance standards for clients that may consider leaving their car home for a more seamless and smooth public transport ride. It is expected that in the following years, new shared mobility services not explored by the market until the moment will emerge and take a market segment of the complex urban mobility ecosystem.

This analysis explores the potential pathways of a massive adoption of shared mobility solution to replace mainly private car mobility and bridge the gap between private mobility and conventional public transport in motorised mobility. Figure 1 presents the main attributes of the shared services tested in ITF shared mobility studies and their comparison against current private or public transport.

Three shared transport services, Shared Taxi, Taxi-Bus and Carpooling are used to assess the impact of shared mobility services. These modes replace current motorised modes and serve as a feeder to the existing heavy public transport lines (rail and metro) lines. Shared Taxi is an on-demand door-to-door service with up to six people sharing the vehicle. It can be booked in real time and moves along dynamically optimised trajectories with detours and travel times matching the pre-set constraints. Taxi-Bus is a street-corner-to-street-corner service in a mini-bus of up to 8 or 16 people with at least 30-minutes advanced reservation time. Carpooling explores the private car fleet existent in cities, allowing car drivers to drive to a parking station, leave their car parked, and take one single vehicle towards a location within a walking distance from every rider's final destination. Taxi-Bus also moves along dynamically optimised routes between designated stops. The first two shared services offer either direct transfer-less trips or serve as a feeder service delivering the user to a rail station if rail connects to the destination without transfers. The feeder service is specified as a pre-booking system with certain booking rules and walk access constraints in the case of Taxi-Bus. The feeder services serve rail trips, for which one station is within walking distance from either origin or destination. This means that the entire trip would have one transfer and include two legs: the one by a shared mode serving one end of the trip and the one by rail. An origin-destination (OD) pair poorly served at both ends leads to a direct Taxi-Bus or a Shared Taxi service.

Figure 1. **Qualitative comparison of transport modes**

Service type	Service quality: Access	On-board time	Waiting	Transfers	Comfort	Price
Private Car	★★★★	★★★★★	★★★★★	★★★★★	★★★★★	★
Public transport (and/ or)	★★	★	★	★★	★★	★★★★★
Shared Taxi	★★★★★	★★★★	★★★★	★★★★★	★★★★	★★
Taxi-Bus	★★★	★★★	★★★	★★★★★	★★★★	★★★
Feeder service to rail, ferry or BRT	★★★	★★★★	★★	★★★★	★★★	★★★★
Carpooling	★★★	★★★	★★★	★★★★	★★★	★★★

Legend:

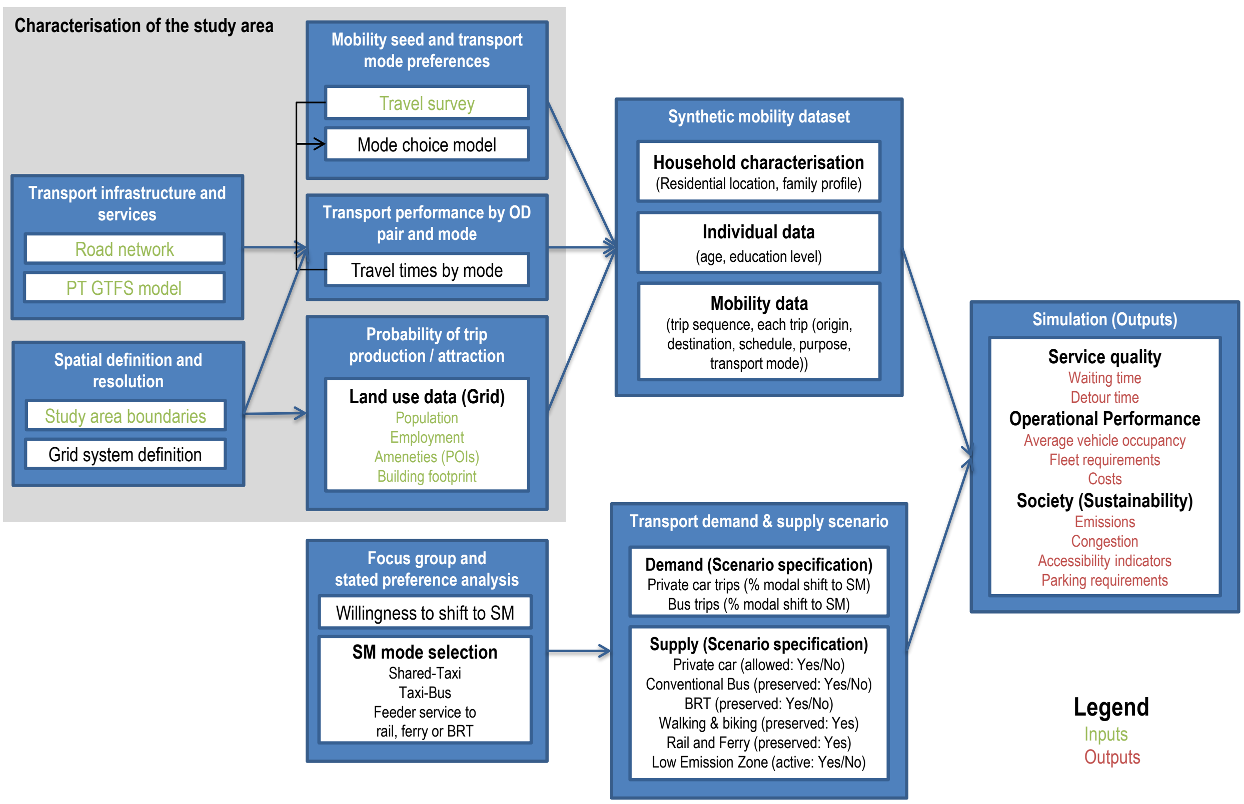
Comparative modes performance rating

★	Very low performance
★★	Low performance
★★★	Average performance
★★★★	High performance
★★★★★	Very high performance

The rise of shared mobility services has generated debate in cities around the world about their regulation, interaction with the current players in the system (e.g. taxi market), safety implications, and how they influence travel behaviour. Some initial studies reveal inconclusive findings regarding the impacts of shared mobility uptake. While some studies suggest that shared services help reduce vehicle ownership and increase use of public transit, others evidence that the early adopters of these services are unsatisfied public transport users, which adds traffic to already congested street under unregulated vehicles movement to search for clients. Furthermore, the short term effects in mode choice and medium term effects on car ownership may not compensate the long term effects of expanding the accessibility and enhancing urban sprawl if policies are not put in place to avoid it.

For this analysis, a thorough review of the literature in the field was undertaken aiming at extracting the observed or expected impacts of shared mobility adoption in parallel with the analysis of shared mobility simulation outputs using the ITF shared mobility simulation model. The ITF framework of analysis of shared mobility is presented in Figure 2. The framework contains several steps to conceive a simulation model and a scenario design platform to test potential of optimized sharing solutions to provide citizens with a more flexible, comfortable and available public transport alternative, overcoming inconvenience of conventional public transport. This would encourage the shift of citizens to more sustainable solutions compared with the use of private cars, which are very inefficient in terms of occupancy rates and vehicle usage, both in space and time. Using vehicles more efficiently will, in turn, lead to a reduction in congestion, social exclusion, road accidents and to the more efficient use of public space and better air quality.

Figure 2. **Shared mobility modelling framework**



Notes: PT- Public Transport; OD – Origin-Destination; SM – Shared Mobility.

Literature review

Several studies in recent years have explored the impact of shared mobility penetration in urban mobility market. Some studies focus more in current observed impacts of standard TNC in the market, mobility and environmental performance indicators (S. A. Shaheen et al., 2017), while other are more prospective, either use simulation based experiments to assess the adoption of shared mobility solutions at large scale (Ciari et al., 2013; Fagnant and Kockelman, 2016; Liu et al., 2017; Spieser et al., 2014; Zachariah et al., 2013), or are expert analysis assessments of aggregate impacts of massive shared mobility adoption in different urban contexts (R. Clewlow and Mishra, 2017; Fulton, 2018; Ronald et al., 2017; S. Shaheen et al., 2015).

The analysis of the development trends and observed mobility impacts of carsharing, ridesharing and new TNC services has focused on the changes on mode choice, the resulting observed motorised mobility (e.g.

travelled vehicle kilometres - vkm) and changes in car ownership. Some literature available summarised in S. A. Shaheen et al. (2017) evidence contradictory results. While there are some positive effects on car mode choice replacement, a significant share of the users of these services come from unsatisfied public transport users or non-motorised transport that switched to this mode for medium distance travel. Furthermore, especially in TNC services but also in carsharing services, the relocation activities of drivers generate larger additional vkms than previously (Bliss, 2017b, 2017a) in some cities with large fleets. Regarding car ownership, some analysis after a five years period have demonstrated a positive effect on reducing car ownership and increase public transport use in errand trips (S. A. Shaheen et al., 2017).

When we analyse simulation based models, as the ones developed by ITF for several cities (ITF 2015, 2016, 2017a, 2017b, 2017c, 2018a, 2018b), the results observed are quite aligned with the ITF ones. When focusing on shared autonomous vehicles for single rider and sequentially used, the results are positive in reducing car fleet to values between 3% and 10% of current, but less effective in reducing vkm and CO_2 emissions between 3 to 10 percent (Fagnant and Kockelman, 2016; Spieser et al., 2014; Zachariah et al., 2013). The interaction with public transport has been also explored in large scale simulations, showing a potential for heavy public transport (e.g. rail, metro) to increase their ridership by being fed by shared mobility options more efficiently (Iacobucci et al., 2017; ITF, 2017c, 2017a, 2017b).

Most of these large scale studies focus mainly in individual mobility been provided by a shared vehicle but as door to door services and never explore a more on-demand real time bus services. As car occupancy rates increase from around 1.2 to average 2.1 there are some savings obtained. Yet, as some additional kilometres are also introduced (approximately 20 to 30 percent) the observed savings in vkms are quite limited, with savings in CO_2 emissions dependent on the vehicle fleet turnover increase (ITF, 2016). If larger shared vehicles are used, producing average occupancy rates greater than six passengers, the savings are much stronger ranging between 25 to 60 percent (Alonso-Mora et al., 2017; ITF, 2017c).

All these studies evidence a significant change in accessibility by private car. This could ultimately lead to some medium term changes in trip production factors, but more importantly in residential and business location strategies that could lead to sprawl in the long term. This fact could lead to loss of all the estimated benefits and reductions of vkms and CO_2 emissions obtained due to the introduction of shared mobility(Rode et al., 2017). Policies might be required in urban areas to ensure retaining of the benefits (Karim, 2017).

Other long term assessments try to evaluate aggregately the role of shared mobility and their interaction with other innovations in shaping urban mobility in different regions of the world. Fulton (Fulton, 2018) explores the interaction of what he designates as three revolutions in urban transportation that are underway: vehicle electrification, automation, and shared (on-demand) mobility. The results evidence that an alignment of these three innovations, the measures in urban planning, and transport demand measures (TDM) containing the effects of urban sprawl and additional trip production can allow achieving the 1.5 degree scenario (Paris agreement 2015).

ITF has developed in the recent years set simulation-based studies on different cities using the same methodological framework presented above in Figure 2. These studies focus on the city of Lisbon (ITF, 2015, 2016), the Lisbon metropolitan area (ITF, 2017c), the metropolitan area of Helsinki, Finland (ITF, 2017b), the metropolitan area of Auckland, New Zealand (ITF, 2017a), the Greater Dublin Area, Ireland (ITF, 2018a) and the metropolitan area of Lyon, France (ITF, 2018b). More recently, a dynamic test in cities of OECD countries showed that the expected results of Shared Mobility can be very sensitive of the local context (Tikoudis et al., 2021).

Evidence from the cities analysed under the ITF Shared Mobility Framework

Analysing the differences in the land uses, transport supply and local conditions and culture is important to understand the mobility changes after massive adoption of shared mobility and replacement of private mobility by shared services.

Land use layouts of cities define their needs of motorised mobility and average travel distances. Density and land use mixture but also the commuting structure of a metropolitan area may set the city mobility profile. Observing the cities analysed with the ITF shared mobility model, Lisbon prevails by its density and land use mixture, Auckland and Dublin show a greater urban sprawl, and Helsinki has a certain urban mono-functionality.

Table 1. **Land use characterisation of the ITF shared mobility case studies**

City	Study area size (total / active)	Population density (inhab. / sqkm – total / active surface)	Land use mixture (avg. entropy index)	CBD influence radius*
Auckland	2 233 / 986	582 / 1 318	0.32	17.5
Dublin	6 988 / 1 047	258 / 1 720	0.36	16.8
Helsinki	770 / 639	1 414 / 1 703	0.29	20.6
Lisbon	3 015 / 999	929 / 2 802	0.53	8.9
Lyon	532 / 512	2 518 / 2 616	0.48	12.6

* measured as the distance to reach three times the inhabitants of the CBD employees

Other key elements are transport infrastructure and public transport services provision. Among the cities studied, Helsinki clearly stands out from the performance of its public transport system followed by Lyon. Auckland public transport provision is considerably lower than in the other cities studied even when compared with Dublin study area, which encompasses the whole region including several rural areas. Regarding road infrastructure availability the differences between the cities are smaller with the exception of Auckland that also presents lower high capacity network density.

Table 2. **Transport infrastructure and services characterisation of shared mobility case studies**

City	Highways network density (km/sqkm)*	Heavy PT infrastructure (km / 1000 inhab.)	PT service provision (seat-km heavy PT / 1 million inhab.)	Connectivity PT (avg. linear speed for trips > 1km) **	PT / PC travel time ratio (trips > 1km)
Auckland	0.2	0.1	3.7	8.0	2.8
Dublin	0.4	0.07	4.9	6.7	2.7
Helsinki	0.7	0.21	16.2	16.1	1.0
Lisbon	0.5	0.14	6.7	7.9	3.1
Lyon	0.8	0.15	9.8	12.1	1.9

* Highways are all road links with speed greater than 80 km/h.

** It includes 10 minutes penalty in the calculation for each transfer by public transport

The previous characteristics set the main mobility and accessibility ecosystem that determines the observed car ownership rates (influenced also by income availability) and the resulting transport mode choice. While density and size of the area can promote non-motorised travel, also car ownership allied with poor public transport provision and urban sprawl can lead to car-oriented mobility. The significant presence of bus in Lisbon and Helsinki evidence that some citizens, either due to financial constraints or personal options related with car ownership, do currently use bus instead of car. This fact may be very important to assess the comparative advantage of shared mobility compared with the current transport options. Shared mobility may be just attractive from an environmental perspective if some of the bus users become early adopters and if the occupancy rate of shared vehicles is comparable to the one of bus.

Table 3. **Travel mode choice and car ownership characterisation of shared mobility case studies**

City	GDP per capita (USD/inhab.)	Car ownership (cars / 100 inhab.)	Non-motorised transport (%) *	Heavy public transport (%) **	Light public transport (%) ***	Private car (%) ****
Auckland	54 178	680	14	1	3	82
Dublin	56 971	350	30	5	8	57
Helsinki	49 364	320	32	12	15	41
Lisbon	32 434	217	19	12	20	49
Lyon	32 213	400	40	13	6	41

* includes walking and bicycle.
** includes rail, metro, bus rapid transit (BRT), light rail transit (LRT) and ferry.
*** includes bus and tram.
**** includes car, taxi and motorcycle, both as a driver and as a passenger.

The observed activity patterns, vehicle fleet composition and transport modal choices of citizens define the daily generation of transport related CO_2 emissions. This initial mobility carbon intensity is then compared with the one resulting from shared mobility scenario. This scenario considers that all private car and bus trips are replaced with trips by shared services, adjusted to the local context. For that a stated preferences survey was conducted assessing natural preferences in a new supply scenario with no cars and no buses and shared mobility running ether as direct services or feeding heavy public transport.

Table 4. **Daily transport related CO_2 emissions of shared mobility case studies (kg/inhab.)**

City	Current case	Tested scenario
Auckland	6.0	2.7
Dublin	3.1	2.1
Helsinki	2.5	1.8
Lisbon	3.5	1.6
Lyon	2.9	1.5

The results show that some cities that departed from a better carbon intensity performance are surpassed by other cities when shared mobility is introduced as a new alternative to complement the existent public transport supply. These benefits that shared mobility is able to introduce are mainly due to four factors:

- **Land use efficiency**. This abstract concept relates to the capacity of cities produce dense and land use mixture settings that will potentiate non-motorised travel but also either shorter trips or more efficient occupancy of public transport. The ability of citizens of Lisbon easily reach a train or metro station and reach easily the final destination leads to a significant share of users who prefer use shared mobility as an access mode instead of a door-to-door service.

- **Public transport services performance**. The existence of good public transport services in the city is a key element for an environmental friendly mobility. A system that allows users to reach destinations efficiently with similar travel times to car, small waiting times and smooth integration between services is what is intended. Identify the segments and locations where shared mobility can help enhancing the system further and aid providing these services more efficiently from an operator's perspective.

- **Heavy public transport network coverage.** The proximity and connectivity within the heavy public transport network is also very important. Shared mobility can provide a very efficient last mile in small vehicles and feed users into the point of the public transport network that would reduce most of their transfers' penalty.

- **Activity patters.** Presenting a more balanced activity distribution in the city allows preserving good efficiency in matching users into shared vehicles and increasing the occupancy rates of vehicles in off peak periods. While vehicles during peak periods have high load factors, in some cities the off-peak periods produce similar outputs to the individual car. This becomes more relevant in more sprawled cities such as Auckland, where the lack of travel during some periods of the day limits the ability of providing efficient shared mobility services.

The results obtained in the tested scenarios of the five case studies were used to calibrate a model to estimate the daily carbon intensity (kg CO_2/inhab.) under different *city layout*, *transport supply* and *shared mobility market adoption*. The model contains the variables presented in Table 5

Table 5. **Explanatory variables used in the carbon intensity model**

City layout (land use characteristics and mobility patterns)	Transport supply (public transport and road provision)	Shared mobility market adoption (private car and bus users adoption)
Average trip distance (km)	Highways network density (km/sqkm)	Share of users of conventional bus * (%)
Case study area size (skm)	Service provision (seat-km heavy PT per 1 million inhabitants)	Share of users of high performance bus (%)
Non-motorised transport (%)		Share of remaining car users ** (%)
Population density (inhab. / sqkm)		

* High performance is considered either a BRT or buses with a high level of service (BHLS) or bus service with headway lower than 7.5 minutes. The remaining bus is considered conventional.
** This variable measures the resulting car modal share after the adoption of shared mobility by part of the original demand defined in the input scenario.

Additionally, car ownership is included in the resulting model as a societal variable that encompass several elements as the income level of the city and the attitude of residents regarding car. This may indicate the potential resistance of shift from private mobility to more shared, influencing the potential success of higher vehicle occupancy solutions of shared mobility alternatives.

The model calibration with this input data was performed using 26 scenarios tested in the different shared mobility studies that provided comparable results for calibration outside the specific study areas. For these reason, scenarios that considered and modelled a specification of a low emission zone (LEZ) with car use restrictions were kept out of this analysis due to the difficulty to translate this reality to all cities in the world without studying their particular geographical configuration in detail.

The linear regression model was calibrated in two steps to avoid collinearity in *City layout* and *Transport supply* variables. First, a principal components analysis was performed to ensure orthogonality between the variables (no correlation) with the results rotated through a Varimax procedure.

The developed procedure extracted two orthogonal variables, which explained 65% of the six original variables. The results are summarised in Table 6, showing the variables with higher loads for the two factors. The statistical tests obtained reveal an acceptable data reduction (Kayser-Meyer-Olkin (KMO) measure of 0.64) and a significant Bartlett sphericity test. The relevant loadings that characterise each factor are highlighted to understand the designation of each of the factors (PA1, PA2).

The first factor (PA1) is characterised by strong public transport provision and low non-motorised transport and private car infrastructure provision. This factor designated "*public transport centred mobility*". The strong non-motorised mobility in a dense urban context with shorter trips but in presence of good motorway network influences the second factor. This factor named "*dense urban context*". The two factors indicate two non-conflicting but different objectives of urban and transport planning: the improvement of transport in favouring public transport in spite of private car, while the second refers to developing of dense land use environments that lead to shorter and more non-motorised travel.

Table 6. **Principal components rotated variables scores for the extracted factors**

Variable	PA1	PA2
Highways network density (km/sqkm)	**-0.66**	**0.75**
Service provision (seat-km heavy PT per 1 million inhabitants)	**1.04**	-0.07
Population density (inhab. / sqkm)	0.21	**0.77**
Non-motorised transport (%)	**-0.67**	**0.68**
Average trip distance (km)	0.55	**-0.68**
Case study area size (skm)	0.54	-0.03

The scores of these two case study contextual factors along with car ownership of each city and the shared mobility market adoption variables where calculated for the 26 scenarios assessed. These explanatory variables were then used to calibrate a linear regression model with carbon intensity (kg CO_2/inhab.) as dependent variables. The obtained results are presented in Table 7. The model does not present any collinearity problems between variables and has a very high goodness of fit (adjusted $R^2 = 0.94$). These results indicate a quite accurate ability of the model in predicting the simulated values for the 26 tested scenarios used for the calibration. The model was not developed to be zero truncated to ensure only positive estimates but may be considered for forecasting exercises specially under technological adaptations of the motorised urban fleet with no tank-to-wheel emissions (e.g. electric vehicles or hydrogen vehicles).

Table 7. **Results of daily carbon intensity regression model calibration**

Explanatory variable	Coefficients	Standard Error	t-stat	p-value
Intercept	1.626	0.506	3.211	0.006
Share of remaining car users (%)	3.379	0.272	12.413	0.000
Share of users of conventional bus (%)	0.322	1.761	0.183	0.858

Share of users of high performance bus (%)	-1.766	1.854	-0.953	0.356
PA1 (“public transport centered mobility”)	-0.112	0.121	-0.925	0.369
PA2 (“dense urban context”)	-0.269	0.145	-1.857	0.083
Car ownership	0.001	0.001	1.244	0.233

The estimated model allows us to estimate an elasticity of the dependent variable to the available explanatory variables. The results are shown in

Table 8 presenting interesting insights:

1. As expected, the reduction of the share of car mobility presents the strongest factor for CO_2 mitigation. This elasticity is, in presence of fleet composition, mainly dominated by characteristics of combustion engines.

2. Reducing car fleet ownership, good population density, public transport provision and high non-motorised modal shares are the main factors that may help mitigating CO_2 emissions in urban contexts. All these measures are aligned with the concepts of transport oriented development (TOD) and travel demand management (TDM) (Cervero et al., 2017).

Table 8. **Carbon intensity elasticities to model explanatory variables**

Explanatory variable	Elasticity
Share of remaining car users (%)	0.39
Share of users of conventional bus (%)	0.04
Share of users of high performance bus (%)	-0.05
Highways network density (km/sqkm)	-0.07
Service provision (seat-km heavy PT per 1 million inhabitants)	-0.15
Population density (inhab. / sqkm)	-0.16
Non-motorised transport (%)	-0.14
Average trip distance (km)	0.08
Case study area size (skm)	-0.09
Car ownership	0.15

Some adjustments need to be included in the model to accommodate the application in different world regions with different vehicle fleet standards, and the changes in fleet composition resulting from technological development into cleaner energies:

1. The intercept of the equation has to be adjusted proportionally to the vehicle.km weight CO2 intensity of different countries when compared to current European standards used in the model calibration. This is true both for different world regions and for estimated future vehicle fleets.

2. In three input variables related to motorised vehicles (Share of remaining car users (%), Share of users of conventional bus (%) and Share of users of high performance bus (%)) , the input shares should also be corrected proportionally to the equivalent 2015 CO_2 intensity of European

fleet composition standards to account for differences in vehicle fleet across countries and periods.

Other element that should be incorporated to the model when forecasting is the double effect of people leaving their car at home and using shared mobility, which have been already measured in the literature, is car ownership reduction. Some recent studies, under much more incipient experiences of carsharing and TNC services, evidenced that the elasticity of car ownership to shared mobility modal share is approximately -0.2 (Cervero et al., 2007; Circella et al., 2018; ITF, 2017b, 2017a). This fact is taken into account in the forecasting model by reducing car ownership 0.2% by each 1% of reduction of car modal share variation.

Policy analysis in different urban contexts

The developed carbon intensity model estimated as a function of urban characteristics, transport supply and shared mobility adoption rate, was also tested in all regions of the world. The following scenarios were tested for the base year of 2015:

- **Baseline scenario**: The CO2 emissions are obtained directly from the ITF urban mobility model.
- **Scenario partial adoption**: 20% of private car mobility is replaced by shared mobility services in all cities of the world.
- **Scenario full adoption**: All private car conventional bus trips are replaced with trips by shared mobility services in all cities of the world;

No additional scenarios regarding technological changes are performed. Yet, analysis of potential technical changes with the emergence of electric vehicles and increase of their range might also be tested.

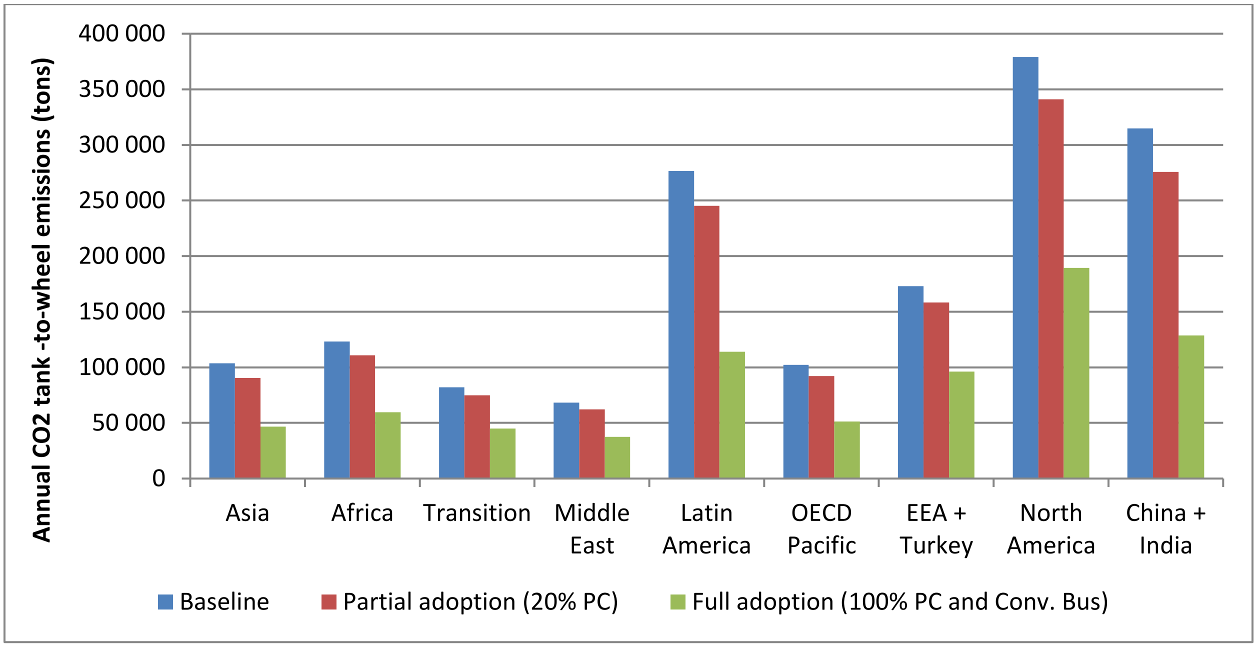
The estimated results in terms of annual tons of CO2 tank-to-wheel emissions are compared by world region to the baseline in Figure 1. The results show that already for 2015 the drastic adoption of shared mobility by replacing conventional bus by on-demand bus solutions. Also, all private car mobility by shared services may have a very strong effect on reducing CO_2 emissions, especially in China plus India and in Latin America due to emerging private car fleets that are replaced by shared mobility options and the high densities in main cities. The high densities ensure a significant share of non-motorised mobility and the use of shared mobility to feed to existent heavy public transport network, which is already in place (e.g. metro, railway, BRT and LRT).

The tested partial adoption scenario in all regions presents already some interesting results. Most of the cities could reduce their CO_2 emissions between 5% and 15%. These results are quite encouraging since, as the focus groups ran by the ITF in the study areas showed (ITF 2017a, 2017b, 2018a), 20% of adoption from car users might be already possible to achieve if low cost and quality of service is ensured. Nevertheless, this scenario considers that all non-motorised transport and public transport users preserve their modal options. The current experiences regarding the early adopters of shared mobility have showed to be more close the public transport and non-motorised transport (R. R. Clewlow, 2016), which evidences the need of targeted measures to preserve the public transport ridership and attract private car users.

The ranges of changes for the whole world for the full adoption scenario vary between 40% and 60% for aggregate regions, which is aligned with the savings assessed for the studied cities in the ITF shared mobility studies (ITF, 2017c, 2017b, 2017a). Nonetheless, some cities that have already a very good public transport system or a high non-motorised transport modal share can produce more limited savings (less than

30%) as North European cities with good public transport provision and cities with high non-motorised transport culture (e.g. Amsterdam, Helsinki).

Figure 3. **Results of daily carbon intensity regression model calibration**



Summary and conclusions

Massive adoption of shared mobility solutions has a significant potential in helping to achieve the urban decarbonising goals if their main long term drawbacks are addressed with targeted policies. The study showed that CO_2 emission reduction strongly depends on the remaining car share, car ownership, urban density and public transport provision, and the dense and fast-growing motorised developing economies have more potential for the reduction. Anticipation of the potential effects of shared mobility in the urban mobility market will be a fundamental element of design of urban policies towards the goal of more sustainable urban mobility.

Potentially shared mobility can reduce global costs of mobility, decrease significantly the access times by improving public transport connections, and to mitigate congestion problems. Yet, the potential of this reduction can be depleted if citizens increase their mobility, relocate further and promote the reduction of urban density, which would lead to more activities or longer journeys for the same individual travel time budget. This needs to be addressed by targeted land use policies and by different pricing of mobility that favours significantly shorter travel compared to long commuting travel.

The interaction of shared mobility with electric mobility and self-driving technologies can even potentiate a faster penetration of services at lower costs and reduce more strongly car ownership rates. Yet, the use of these technologies should be properly addressed as self-driving can promote indirectly more frequent and longer journeys since travelling may become a more productive or useful activity in itself.

Acknowledgements

This project was financed by the Corporate Partnership Board of the International Transport Forum for the development of the model and the application to the city of Lisbon, Portugal; as a Case-Specific Policy Analysis by the member countries in the case of Dublin, Ireland and Helsinki, Finland and the ClimateWorks Foundation in the case of Lyon, France.

References

Alonso-Mora, J., S. Samaranayake, A. Wallar, E. Frazzoli and D. Rus (2017), "On-demand high-capacity ride-sharing via dynamic trip-vehicle assignment", *Proceedings of the National Academy of Sciences*, Vol. 114/3, pp. 462–467, https://doi.org/10.1073/pnas.1611675114.

Bliss, L. (2017a), "Stop Asking Whether Uber Is Transit's Enemy", CityLab, https://www.citylab.com/transportation/2017/02/uber-lyft-transportation-network-companies-effect-on-transit-ridership-new-york-city/517932/ (accessed September 15, 2017).

Bliss, L. (2017b), "The Ride-Hailing Effect: More Cars, More Trips, More Miles", CityLab, https://www.citylab.com/transportation/2017/10/the-ride-hailing-effect-more-cars-more-trips-more-miles/542592/ (accessed September 15, 2017).

Cervero, R., A. Golub and B. Nee (2007), "San Francisco City CarShare : Longer-Term Travel-Demand and Car Ownership Impacts", *Transportation Research Record*, Vol. 1992/May, pp. 70–80, https://doi.org/10.3141/1992-09.

Cervero, R., E. Guerra and S. Al (2017), "Toward Sustainable Urban Futures", in *Beyond Mobility*, Island Press.

Ciari, F., N. Schuessler and K. W. Axhausen (2013), "Estimation of Carsharing Demand Using an Activity-Based Microsimulation Approach: Model Discussion and Some Results", *International Journal of Sustainable Transportation*, Vol. 7/1, pp. 70–84, https://doi.org/Doi 10.1080/15568318.2012.660113.

Circella, G., F. Alemi, K. Tiedeman, S. Handy and P. Mokhtarian (2018), *The Adoption of Shared Mobility in California and Its Relationship with Other Components of Travel Behavior*, .

Clewlow, R. and G. S. Mishra (2017), "Disruptive Transportation: The Adoption, Utilization, and Impacts of Ride-Hailing in the United States", *Ucd-Its-Rr-17-07*, October.

Clewlow, R. R. (2016), "Shared-Use Mobility in the United States: Current Adoption and Potential Impacts on Travel Behaviour", *In Annual Meetings of the Transportation Research Board, Washington DC. Vancouver*, .

Fagnant, D. J. and K. M. Kockelman (2016), "Dynamic ride-sharing and fleet sizing for a system of shared autonomous vehicles in Austin, Texas", *Transportation*, pp. 1–16, https://doi.org/10.1007/s11116-016-9729-z.

Fulton, L. M. (2018), "Three Revolutions in Urban Passenger Travel", *Joule*, , https://doi.org/10.1016/j.joule.2018.03.005.

Iacobucci, J., K. Hovenkotter and J. Anbinder (2017), "Transit Systems and the Impacts of Shared Mobility", in *Disrupting Mobility*, (pp. 65–76)Springer.

ITF (2018a), "Shared Mobility Simulations for Dublin", *International Transport Forum Policy Papers*, 72.

ITF (2018b), "Shared Mobility Simulations for Lyon", *International Transport Forum Policy Papers*, 73.

ITF (2017a), "Shared Mobility Simulations for Auckland", *International Transport Forum Policy Papers*, 40, https://doi.org/https://doi.org/http://dx.doi.org/10.1787/5423af87-en.

ITF (2017b), "Shared Mobility Simulations for Helsinki", *International Transport Forum Policy Papers*, 64.

ITF (2017c), "Transition to Shared Mobility: How large cities can deliver inclusive transport services", *International Transport Forum Policy Papers*, Nº 33, https://doi.org/10.1787/b1d47e43-en.

ITF (2016), "Shared mobility: innovation for liveable cities", *International Transport Forum Policy Papers*, Nº 21, https://doi.org/10.1787/24108871.

ITF (2015), *Urban Mobility System Upgrade: How shared self-driving cars could change city traffic*, OECD Publishing.

Karim, D. M. (2017), "Creating an Innovative Mobility Ecosystem for Urban Planning Areas", in *Disrupting Mobility*, Springer.

Liu, J., K. M. Kockelman, P. M. Boesch and F. Ciari (2017), "Tracking a system of shared autonomous vehicles across the Austin, Texas network using agent-based simulation", *Transportation*, Vol. 44/6, pp. 1261–1278, https://doi.org/10.1007/s11116-017-9811-1.

Rode, P., G. Floater, N. Thomopoulos, J. Docherty, P. Schwinger, A. Mahendra and W. Fang (2017), "Accessibility in Cities: Transport and Urban Form", in G. Meyer & S. Shaheen (Eds.)*Disrupting Mobility: Impacts of Sharing Economy and Innovative Transportation on Cities*, (pp. 239–273)Springer International Publishing, https://doi.org/10.1007/978-3-319-51602-8_15.

Ronald, N., Z. Navidi, Y. Wang, M. Rigby, S. Jain, R. Kutadinata and R. Thompson (2017), "Disrupting Mobility", *Disrupting Mobility*, pp. 275–290, https://doi.org/10.1007/978-3-319-51602-8.

Shaheen, S. A., A. P. Cohen, I. Zohdy, W. Berman, United States. Federal Highway Administration. and Booz Allen & Hamilton. (2017), *Shared mobility : current practices and guiding principles*, .

Shaheen, S., N. Chan, A. Bansal and A. Cohen (2015), "Shared Mobility a Sustainablity and Technology Workshop: Definition, Industry Development and Early Understanding", *University of California Berkeley Transportation Sustainability Research Center*, pp. 30.

Spieser, K., K. Treleaven, R. Zhang, E. Frazzoli, D. Morton and M. Pavone (2014), "Toward a systematic approach to the design and evaluation of automated mobility-on-demand systems: A case study in Singapore", in *Road Vehicle Automation*, (pp. 229–245)Springer.

Tikoudis, I., L. Martinez, K. Farrow, C. García Bouyssou, O. Petrik and W. Oueslati (2021), "Ridesharing services and urban transport CO2 emissions: Simulation-based evidence from 247 cities", *Transportation Research Part D: Transport and Environment*, , https://doi.org/10.1016/j.trd.2021.102923.

Zachariah, J., J. Gao, A. Kornhauser and T. Mufti (2013), "Uncongested mobility for all: A proposal for an area wide Autonomous taxi system in New Jersey", in *Transportation Research Board Annual Meeting*, .

Summary of activities within EDITS network

The project has received funding from the Research Institute of Innovative Technology for the Earth (RITE) under subcontract agreement D06710.

Introduction

This report summarizes a contribution of the ITF to the Energy Demand changes Induced by Technological and Social innovations (EDITS) research community. The aim is to provide an analysis how demand disruptions in the transport sector have been incorporated in the ITF modelling framework. This introduction aims at help on the assessment and creation of a common framework of communication with the global energy models as IIASA MESSAGE model.

The reports describes the ongoing activities of ITF within the Transport Working Group but also the linkages with the other Working Groups.

Background

EDITS carries out research to assure the transfer of methodological and modelling innovations across demand-side models, and builds an interactive research and policy network. The project identifies gaps and potentials to enhance novel service delivery models or policy interventions on climate mitigation and the SDGs.

Because of the high heterogeneity of consumers and the multitude of demand types (food, shelter, mobility, communication, etc.) the theoretical understanding and modelling of "demand" (outside aggregated simplistic formulation) remains limited and fragmented, as are resulting capabilities to propose and to assess demand-side policy interventions from the twin angle of climate mitigation as well as of promoting the SDGs.

The main objectives of EDITS are:

- to create a research community with a focus on end-use, demand-side perspectives that furthers dialogue and cross-fertilisation of research and policy analysis through the sharing of novel data, novel concepts, methodologies and policy analyses.
- to improve the state-of-art of demand modelling in environmental and climate policy analysis, via methods and model intercomparisons and assisting the transfer of conceptual and methodological improvements across disciplines, sectors, and environmental domains.
- to better inform policy via structured model experiments and simulations that assess potential impacts, barriers, as well as synergies and trade-offs to other SDG objectives of demand-side policy interventions, particularly in novel fields and service provision models such as digitalization, sharing economy, or the integration of SDG and climate objectives in synergistic policy designs.

EDITS focuses on both the human and the technical resources by launching an expert network and a demand-side model comparison exercise.

ITF is providing expertise and contributing in the transport sector by providing state of the art and practise tools and insights of the role of innovations and policies on controlling or reducing transport activity, the derived energy consumption and CO_2 emissions.

ITF activities 2021

Participation in workshops or other EDITS meetings

ITF participated in the workshops presenting the advances in the working group:

- Participation and contribution to the EDITS annual meeting (9-10 December 2021)
- Presentation of the advancement of the transport working group.
- Participation and contribution to the EDITS quarterly meetings (25 January 2021?, 15 June 2021, ??). Presentation of the advancement of the transport working group.

Joined EDITS Working Groups research

Data group: Participation in the methodology paper on data sharing among models. Setting up the standard description of model data inputs and outputs, to make model components more understandable and highlight potential model connections or gaps.
Narratives group: Participation in meetings and provide feedback about the approach in the transport sector and the connection with the other sectors.
Industry group: Participation as a listener in the meetings to be aware of the approach and linkages to freight demand adaptations.
Buildings group: Participation as a listener in the meetings to be aware of the approach and linkages to land-use implications on urban transport.
Protocol group: Participation as a listener in the meetings to be aware of the approach and linkages to transport working group.

Transport Working Group research

The members of the working group are currently developing a review paper on the demand transformative phenomena in the transport sector. The paper is being developed in a shared file (Overleaf: https://www.overleaf.com/project/61b891b6ca0d05531f5cb762). The paper has currently a temporary title: "Novel transport technology trends and implications for modelling: a review".

ITF specific research to feed into EDITS

ITF has developed in 2021 a set of work dedicated to EDITS to improve the connections with other models, sectors and provide feedback into the narratives working group. We developed for documentation a document that summarises how demand disruptive phenomena are integrated currently in ITF models. This document is titled: "Summary of updates on the modelling tools and outputs to be used by EDITS network".

In order to ensure model exchanges supported by the EDITS community, the ITF updated its global urban passenger model and provided a research paper-format document describing its last version. It especially emphasizes the assumptions and data sources behind the model and explains its structure and connection with other demography, land-use or energy fields of research. The paper is titled: "The 2020 global urban passenger transport model of the International Transport Forum".

Finally, ITF developed an example of the integration of information from a microsimulation model into an aggregate model. The paper introduces into the ITF global urban passenger transport model the learnings from the detailed model and generates estimates of the role of shared mobility in several world regions in the next decades. The document is titled: "Assessment of a demand disruptive phenomena: Shared mobility. How to incorporate simulation-based results and data in aggregate models". This work was also shared with other groups into shared research into a common research paper: "Ridesharing services and urban transport CO2 emissions: Simulation-based evidence from 247 cities" (https://www.sciencedirect.com/science/article/abs/pii/S1361920921002224)

The 2020 global urban passenger transport model of the International Transport Forum

Authorship: Mallory Trouvé, Luis Martinez

*International Transport Forum

This paper aims to present the International Transport Forum (ITF) 2020 global urban passenger transport model and its potential for studying travel demand, transport decarbonisation, and testing policy measures and technology developments. The model assesses transport supply and demand in all regions globally, for more than 9 200 macro Functional Urban Areas. It estimates trips, mode shares, passenger-kilometres, vehicle-kilometres, energy consumption and CO_2, SO_4, NOx and PM emissions for 18 modes[2] from 2015 to 2050, in five-year increments. The current version enables quantifying the impact of 20 policy measures and technology developments specified for each of the 19 regional markets included in the model. In each iteration, the model first updates transport supply characteristics, including information on vehicle ownership, the availability of road infrastructure, public transport, and other mobility services. Second, it generates trips. Third, a mode split module calculates mode shares using a discrete choice model that accounts for cost, time, and accessibility attributes of the different modes. Last, transport emissions are estimated based on vehicle load factors and average vehicle emissions depending on the composition of the local vehicle fleet.

(191 words)

Keywords: Transport modelling, Decarbonisation studies, Socio-economics foresight, policy analysis, urban transport, passenger transport, worldwide analysis

1. Introduction

Urban passenger transport is a subsector of the transport sector focusing on trips made by individuals within a metropolitan area, excluding the study of trips happening outside the urban setting and freight movement. This subsector is heavily linked with land-use and urbanisation studies. According to UN DESA (2019), the urban population is expected to grow by 68% between the reference year 2015 and 2050, putting intense pressure on urban travel demand combined with an urban economic growth pressure, especially in emerging countries. Between 2015 and 2050, the International Transport Forum (ITF) expects the total urban passenger travel demand to be multiplied by 2.6 in(ITF, 2021). This growth in demand has substantial impacts on the transport system, economies, but also on environmental pollution and social wellbeing. Urban passenger transport must be assessed to enable a better understanding of world challenges of sustainable development.

The transport modelling field of research has provided several types of models that enable estimating future levels of demand and pollutant emissions related to the transport sector, specifically to the urban passenger transport subsector. Transport models typically reflect the impact of demographic, economic and infrastructure evolutions on travel demand, quantifying expected travel demand dynamics. These dynamics can be converted into pollutant emissions when jointly considering vehicle fleet characteristics. Most transport modelling theories are derived from concepts described in(Ortúzar and Willumsen, 2011).

In 2017, the ITF disclosed its first version of the global urban passenger transport model in (Chen and Kauppila, 2017),supporting the analysis of the ITF Transport Outlook 2017. The model was employed to quantify the overall subsector's outlook. Since then, the model has experienced several developments, and its potential uses have been expanded to enable more refined policy impact analysis. This paper aims at detailing the last 2020 version of the ITF global urban passenger transport model and its potential for estimating future demand and related sustainability impacts, including potential policy and technology development scenario analyses. It puts forward the main model characteristics, assumptions, and mechanisms for representing future mobility demand and related emissions.

After reviewing the urban passenger transport modelling efforts at a global scale, a presentation of the diverse model inputs is proposed. A third section investigates the overall model structure and how each model block is coordinated with the others, and several model outputs are presented in a fourth section. The fifth section details how policy measures and technological developments are considered within the model, to represent their impacts on the subsector. A final discussion highlights the key elements of the model and how it can be used to pursue a wide set of analyses, aside from the traditional travel demand volume estimation.

2. Modelling urban passenger transport at a global scale

Urban passenger transport is a topic with many different definitions. The notion of urban and city is not consensual. When going into detail, a city does not have the same geographical boundaries depending on the studies: the administrative definition does rarely match the functional definition of an urban area, which keeps evolving (Trouve et al., 2020). The present model relies on the OECD/EC (2020) Cities in the World project definition of cities based on continuous built-up and population densities of 1km square grids. The availability of data at the urban scale is also often limited. While data is regularly collected at the national or city administrative level, it is less at an urban one regularly evolving. As such, collecting data at the urban scale is a complicated process which often needs a lot of estimation from data available at other scales or in other similar cities or countries.

Regarding the modelling theory approach, the ITF global urban passenger transport model stems from a travel demand modelling perspective based on choices from individuals. Other transport models such as the Mobility Model (MoMo) developed by the International Energy Agency (IEA), described in (L. Fulton et al., 2009). The model presents a different approach to urban passenger transport activity, determined by estimated vehicle activity distributions and energy consumption. This approach is common is the energy demand estimation in the energy sector, where individual behaviour is out of the scoope of analysis.. The distinction between these two approaches is key because the topic is not exactly the same: travel demand models consider any trip of individuals located within the limit of an urban area as urban passenger transport, while energy models consider any trip made by an urban type vehicle, which could occasionally happen out of the city limits. These models from the energy sector tend to have a vehicle stock dynamic approach based on the activity, scrappage and renewal of vehicles.

While Integrated Assessment Models (Message model from IIASA, described in(McCollum et al., 2017). combine outputs from diverse fields to analyse total emission and energy consumption, global urban transport models focusing on representing the transport sector are less common. Aside from the ITF model and MoMo, the work conducted in (L. M. Fulton, 2018)and (ITDP and UCDavis, 2021)also provides worldwide modelling for urban passenger transport. Another approach in (Reul et al., 2021) can be to not represent overall passenger transport but simulate a synthetic city to test the evolution of its demand and emissions under different policies.

The ultimate goal of these models is to assess travel demand evolution and related pollutant emissions over time under different scenarios of policy measures and technology developments. While there are more studies at the city level, such as (Martinez and Viegas, 2017)with the case study of developing automated shared mobility systems in Lisbon, Tikoudis et al. (2021) illustrates a use of such global models for assessing the global impact of shared mobility development. Other approaches like Miskolczi et al. (2021) make the analysis with qualitative scenarios and potential for decarbonising the sector.

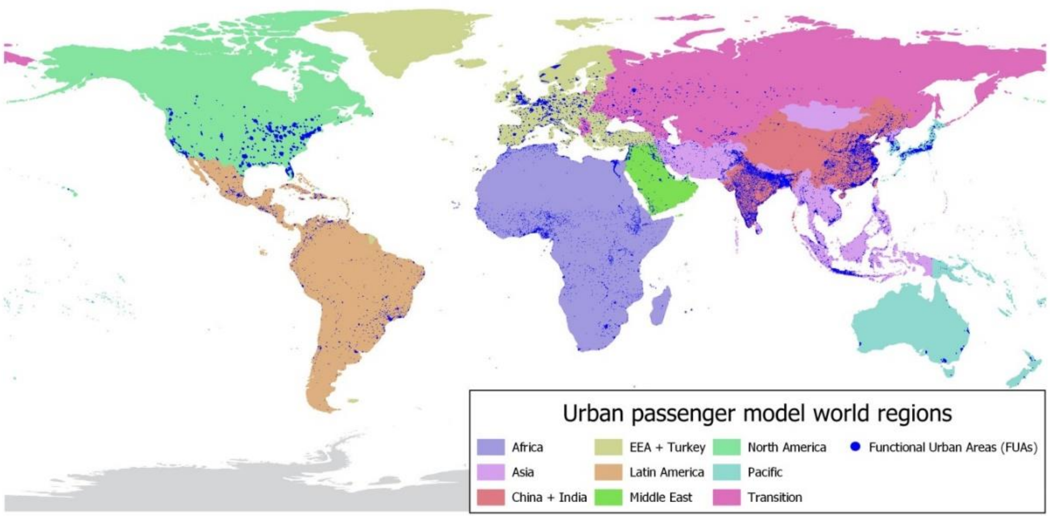
3. Inputs

The inputs of the ITF 2020 global urban passenger transport model can be segmented among five input categories, each highlighting a side of the urban passenger transport system. First geographic data provides the limits of the study field, its geographic composition and the activities available. Second, socio-economic data describes the urban population characteristics. Third, transport supply data characterises the different transport networks available in the study field. Fourth, travel demand data is the key one, only used as an input for the calibration step in the reference year. It focuses on how individuals travel in the urban area and is expressed in volume of travel and trips. Fifth and last, vehicle fleet and environment data connecting travel volumes to transport emissions are also necessary for running the model. While all these data inputs are required for the reference year 2015, the travel demand data is not an input but an output of the model for future years. Most of the time, the data is not available for every urban area, and several extrapolations are made to rebuild unobserved attributes from similar cases (in the same world region or country when available, with similar population or GDP per capita).

Geographic data

The boundaries and areas of each urban area for 2015 considered in this modelling exercise directly come from(OECD, 2020). Each urban area is a macro Functional Urban Area (mFUA): an FUA is the aggregation of 1km grid cells with significant population concentration. In the model, FUAs are aggregated into an mFUA if contiguous and belonging to the same administrative region within a country. Along with this main perimeter description, a city centre can be distinguished from the suburb for the larger mFUAs. OECD/EC (2020) also provides the perimeter of this city centre, also defined on population concentration criteria. A total of 9 234 mFUAs representing all the urban areas over the world are within the scope of this model. The different mFUAs display patterns grouped into 19 world regions built based on similar country cultures and characteristics. The mFUAs and world region are displayed in Figure 1.

Figure 1 Mapping of the macro Functional Urban Areas (mFUAs) and modelling world regions



Socio-economic data

In the ITF global urban passenger model, urban population characteristics are mostly condensed into demographic and economic attributes. The demographic data required is disaggregated at the age (18 age groups: below 1, 1 to 4, 5 to 9… 75 to 79, 80 and over) and gender (female or male) level for each mFUA. Initial 2015 population come from an interpolation of (OECD, 2020), UN DESA World Urbanization Prospect 2018[1] and WorldPop[2] data. Expected death rates, birth rates and international migrations at the country level from the UN DESA World Population Prospect 2019[3] database and 2015 mFUA gender and age composition from WorldPop are collected for calibrating an in-house demographic model. The economic data focuses on Gross Metropolitan Product (GMP) for each mFUA. It is estimated from the economic directorate of OECD country GDP estimations between 2015 and 2050, and NASA Landsat geographical

---

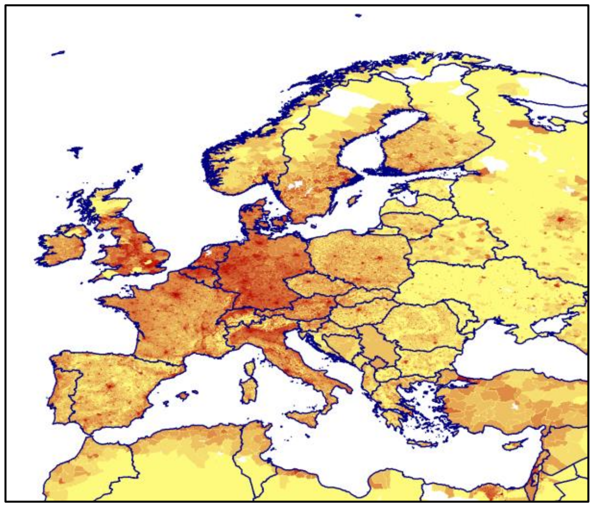
[1] UN Department of Economic and Social Affairs, World Urbanization Prospects 2018, https://population.un.org/wup/

[2] WorldPop 2020 dataset, https://www.worldpop.org/

[3] UN Department of Economic and Social Affairs, World Population Prospects 2019,https://population.un.org/wpp/

distribution of GDP (Nordhaus and Chen, 2016). An example of the GDP distribution is displayed in Figure 2.

Figure 2 Landsat Map of GDP distribution in the European Union



Transport supply data

Characterising the transport networks and setting up initial attributes of the 18 different transport modes listed in Table 1 is key for the core of the transport model. Existing 2015 public transport and road infrastructure data comes from OpenStreetMap[4] and the Global BRT database[5], while service data is obtained from GTFS. They enable getting network length by five link types characterized by their speed, and the number of PT stops by PT mode. Taxi, parking, gasoline, ticket costs and fare information is collected from a wide set of sources[6]. Modal characteristics (i.e. costs, travel time, reliability, access time, waiting time, average number of transfers, speed) for each mode and by distance category (0-1km, 1-2.5km, 2.5-5km, 5-10km, 10-20km, over 20km) are estimated based on these data sets and expert judgement. The evolution of these supply characteristics is implemented based on GDP per capita, population and area, among other explanatory variables.

[4] OpenStreetMap database, https://www.openstreetmap.org/

[5] Global BRT Data, https://brtdata.org/

[6] Main sources include UITP database https://www.uitp.org/data/, EMTA data https://www.emta.com/, generic studies and papers

Table 1 Modes represented in the ITF global urban passenger model 2020

Mode category	Mode	Description
Active mode	Walk	-
Active mode	Bike	Private bicycle
Active mode	Scooter-sharing	Shared electric kick scooter system
Active mode	Bike-sharing	Shared bike and electric bike system
Paratransit	PT-InformalBus	Informal bus system not managed by a public administration
Paratransit	PT-ThreeWheeler	Informal three-wheeler or rickshaw system not managed by a public administration
Private vehicle	Motorcycle	Private motorcycle
Private vehicle	Car	Private car
Public Transport	PT-Rail	Heavy rail system for long distances
Public Transport	PT-Metro	Heavy rail system for short to medium distances
Public Transport	PT-LRT	Light Rail Transit system
Public Transport	PT-Bus	Bus system
Public Transport	PT-BRT	Bus Rapid Transit system
Shared mobility	Taxi	Taxi system
Shared mobility	Ride-sharing	Private ride-hailing system
Shared mobility	Minibus-sharing	Ride sharing system based on high capacity vehicles. Also referred to as Taxi-bus
Shared vehicle	Motorcycle-sharing	Shared motorcycle system
Shared vehicle	Car-sharing	Shared car system

Travel demand data

Travel demand data for 2015 household travel surveys was collected from several ITF country members, as an input to calibrate the main part of the transport model estimating future travel demand data based on the evolution of all the other input data. This data is made of a collection of travel surveys describing mode shares and trip characteristics that the model will try to reproduce.

Vehicle fleet and environment data

Data on vehicle technology pathways comes from two primary sources. For each mode, the vehicle fleet composition (by fuel, engine and vehicle type), respective CO_2 emission factors (tank-to-wheel (TTW) and well-to-tank (WTT)), and vehicle load factors between 2015 and 2050 come from the Mobility Model (MoMo)[7] of the International Energy Agency (IEA). The emission factors of local pollutants (e.g. SO_4, NOx, PM2.5) by mode and fuel type come from the ICCT Transport Roadmap Model[8]. They enable converting travel demand into related emissions, and also have some impact on the modal characteristics.

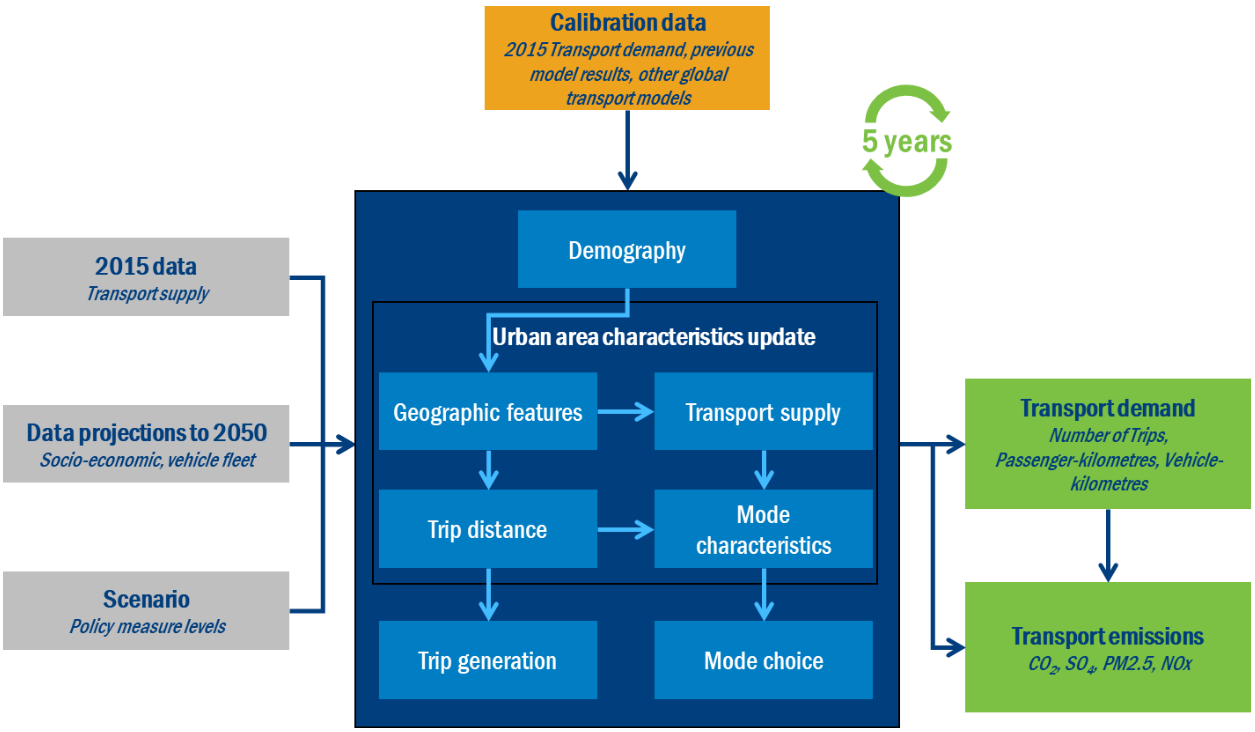
[7] IEA (2020), IEA Mobility Model, https://www.iea.org/areas-of-work/programmes-and-partnerships/the-iea-mobility-model.

[8] ICCT (2019), Transportation Roadmap, https://www.theicct.org/transportation-roadmap (accessed on 13 March 2019).

4. Model structure

The ITF global urban passenger model is organised around several blocks represented in Figure 3: The input blocks include the different types of input required for the model, these inputs are all exogenous; It computes the state of urban passenger transport for all the mFUAs from the base year 2015 to the target year 2050, with 5-year increments.

Figure 3 Structure of the ITF Global Urban Passenger Transport Model 2020



- The input blocks in grey are aggregations of input data categories, which are entirely exogenous to the model. 2015 transport supply data is used as a starting value to set up initial transport supply characteristics within the model, that will evolve based on other indicators in the future, within the model. Data projections from 2015 to 2050 on socio-economic characteristics and vehicle fleet characteristics and emissions are entirely exogenous. Last, the scenario input includes different transport and land-use policy levels, and several societal trends or technology assumptions impacting the development of the metropolitan area or the transport system. This input is used to test the impact of different scenario setting on future transport system states and related emissions.
- The calibration block in yellow illustrates that the 2015 demand data input is not used as a direct input within the model but as calibration values. The model parameters are set to reproduce these travel demand values based on the 2015 data inputs available. Expert analyses on the evolution of the model results are also conducted to ensure a proper calibration over time. This includes comparisons with other international studies on urban passenger transport and previous model version results.
- The core model component blocks in blue are blocks happening within the model process and are endogenous.

First, a demographic module has been set up, estimating the evolution of the population and its composition based on a survival stock model approach. It follows the formula:

Equation 1

$$pop_{a+1,g,t+1}{}^{MFUA} = pop_{a,g,t}{}^{MFUA} \times \left(1 - dr_{a,g,t}{}^{country}\right) + mig_{a,g,t}{}^{national,MFUA} + mig_{a,g,t}{}^{international,MFUA}$$

with $pop_{a,g,t}{}^{MFUA}$ the population of the age category a and gender category g for the time step t in the city $MFUA$; $dr_{a,g,t}{}^{country}$ the average death rate of the age category a and gender category g for the time step t in the $country$; $mig_{a,g,t}{}^{national,MFUA}$ and $mig_{a,g,t}{}^{international,MFUA}$ the respective national and international net population migrations to the city $MFUA$ for the population of the age category a and gender category g for the time step t. Limit formulas for this demographic model are as follow:

Equation 2

$$pop_{0-4,g,t+1}{}^{MFUA} = \sum_{15 \le a < 50} \left(pop_{a,F,t}{}^{MFUA} \times br_{a,g,t}{}^{country}\right) \times \left(1 - dr_{0-4,g,t}{}^{country}\right) + mig_{0-4,g,t}{}^{national,MFUA} + mig_{0-4,g,t}{}^{international,MFUA}$$

and

Equation 3

$$pop_{80+,g,t+1}{}^{MFUA} = pop_{75-79,g,t}{}^{MFUA} \times \left(1 - dr_{75-79,g,t}{}^{country}\right) + pop_{80+,g,t}{}^{MFUA} \times \left(1 - dr_{80+,g,t}{}^{country}\right) + mig_{a,g,t}{}^{national,MFUA} + mig_{a,g,t}{}^{international,MFUA}$$

with $pop_{0-4,g,t}{}^{MFUA}$ and $pop_{80+,g,t}{}^{MFUA}$ the population aged between 0 and 4, and over 80 years old respectively, of gender category g for the time step t in the city $MFUA$; $pop_{a,F,t}{}^{MFUA}$ the population of age a, of gender category F (female) for the time step t in the city $MFUA$; $br_{a,g,t}{}^{country}$ the average birth rate for babies of gender g, for the females of age a for the time step t in the city $MFUA$.

Second, the characteristics of urban areas are updated beginning with spatial geographic features (i.e. area, density), which impacts transport supply (evolving along with the area, density and GDP evolution) and trip distance distribution (based on a utility approach of each trip distance category with a logit distribution), which impacts the mode characteristics in turn.

Equation 4

$$U_d{}^{MFUA} = ASC_d + \lambda_{d,s} \times s^{MFUA} + \lambda_{d,s\_core} \times s_{core}{}^{MFUA} + \lambda_{d,dens} \times dens^{MFUA} + \lambda_{d,dens\_core} \times dens^{MFUA} + \lambda_{d,LU} \times LU^{MFUA}$$

with $U_d{}^{MFUA}$ the utility for the distance bin d; ASC_d the alternative specific constant for the distance bin d of the city $MFUA$; $\lambda_{d,s}$, λ_{d,s_core}, $\lambda_{d,dens}$, $\lambda_{d,dens\_core}$, $\lambda_{d,LU}$, the utility parameters respectively for the MFUA surface s^{MFUA}, the city centre surface $s_{core}{}^{MFUA}$, the MFUA population density $dens^{MFUA}$, the population density of the city centre

$dens^{MFUA}$, and the land-use mixture of the MFUA LU^{MFUA}. The final computation of the shares of each distance bin in the total number of trips can be done with the formula:

Equation 5

$$Share_d^{MFUA} = \frac{\exp(\mu \times U_d{}^{MFUA})}{\sum_{i,U_i{}^{MFUA} \neq 0} \exp(\mu \times U_i{}^{MFUA})}$$

with $Share_d^{MFUA}$ the share of the trips for the distance bin d in the city $MFUA$, μ a standardisation parameter.

Third, the proper travel demand generation steps run with the trip generation and mode choice blocks for each population category. The trip generation is based on a regression including GDP per capita and population category explanatory variables, while the mode choice is based on a discrete choice model sensitive to modal characteristics and population category. The initial availability of a mode alternative for the mode choice within a mFUA and for a distance bin is determined by the existing transport supply and a mode applicability matric by distance bin. Table 2 displays this matrix, with 1 indicating the presence of the mode in the choice set for the related distance bin. This applicability matrix also varies based on the age group of the population and can vary by gender.

Table 2 Illustration of the mode applicability matrix

Mode Applicability by Distance Bin *1: mode available, 0: mode not available*							
	Distance bin id	**0**	**1**	**2**	**3**	**4**	**5**
Mode	**Mode code**	< 1km	1 - 2.5 km	2.5 km - 5 km	5 km - 10 km	10 - 20 km	> 20 km
Walk	M_1	1	1	1	-	-	-
Bicycle	M_2	1	1	1	1	-	-
Motorcycle	M_3	1	1	1	1	1	1
PrivateCar	M_4	1	1	1	1	1	1
Taxi	M_5	1	1	1	1	1	1
PT-Rail	M_6	-	-	1	1	1	1
PT-Metro	M_7	1	1	1	1	1	1
PT-LRT	M_8	1	1	1	1	1	1
PT-Bus	M_9	1	1	1	1	1	1
PT-BRT	M_10	-	-	1	1	1	1
PT-InformalBusDRTv	M_11	-	1	1	1	1	1
PT-ThreeWheeler	M_12	-	-	-	-	-	-
Scooter-sharing	M_13	1	1	-	-	-	-
Bike-sharing	M_14	1	1	1	1	-	-
Ride-sharing	M_15	1	1	1	1	1	1
Motorcycle-sharing	M_16	-	1	1	1	1	1
Car-Sharing	M_17	-	1	1	1	1	1
Minibus-sharing	M_18	-	-	1	1	1	1

The formula for the utility of each mode alternative of the mode choice is computed as follows:

Equation 6

$$\begin{aligned} U_m{}^{a,g,d,MFUA} = {} & ASC_m^{g,market} + \lambda_{m,r}^{market} \times r_m^{MFUA} + \lambda_{m,access}^{market} \times access_m{}^{MFUA} + \lambda_{m,wait}^{market} \\ & \times wait_m^{MFUA} + \lambda_{m,time}^{market} \times time_m^{a,d,MFUA} + \lambda_{m,tr}^{market} \times tr_m^{MFUA} + \lambda_{m,pk}^{market} \\ & \times pk_m^{MFUA} + \lambda_{m,cost}^{market} \times cost_m^{d,MFUA} + \lambda_{m,infra}^{market} \times infra_m^{MFUA} \end{aligned}$$

with $U_m{}^{a,g,d,MFUA}$, the utility of the mode m for the age a, gender g and distance d category of the city $MFUA$; $ASC_m^{g,market}$, the alternative specific constant for the mode m, depending on the gender g category, and on the regional market $market$ to which the mFUA belongs; $\lambda_{m,r}^{market}$, $\lambda_{m,access}^{market}$, $\lambda_{m,wait}^{market}$, $\lambda_{m,time}^{market}$, $\lambda_{m,tr}^{market}$, $\lambda_{m,pk}^{market}$, $\lambda_{m,cost}^{market}$, $\lambda_{m,infra}^{market}$ the utility parameters respectively for the resilience r_m^{MFUA}, time to access $access_m{}^{MFUA}$, waiting time $wait_m^{MFUA}$, travel time $time_m^{a,d,MFUA}$, transfer connectivity tr_m^{MFUA}, parking cost pk_m^{MFUA}, cost $cost_m^{d,MFUA}$, and infrastructure attractiveness $infra_m^{MFUA}$ of the mode m and city $MFUA$

variables; the travel time variable also varies depending on the age a and distance bin d category, and the cost variable by the distance bin d category. In specific cases, the parameters can be found at a more accurate national or city level rather than the market one, which is available by default for all cases.

The final mode shares are computed following the multinomial logit discrete choice formula:

Equation 7

$$Share_m^{a,g,d,MFUA} = \frac{\exp({U_m}^{a,g,d,MFUA})}{\sum_{i,available} \exp({U_i}^{a,g,d,MFUA})}$$

with $Share_m^{a,g,d,MFUA}$ the shares of mode m in the age a, gender g, distance bin category d of the city $MFUA$.

Different mode choice formulas are also employed for the mFUA centre and for its suburb.

- Last, final model outputs are generated by the output blocks. All previous results from the other model blocks are gathered within the Transport demand output block. It provides the overall travel demand in terms of trip number, volume of passenger-kilometre and volume of vehicle-kilometres for each population category, distance category, mode, and 5-year step iteration.

5. Outputs

The results outputted by the 2020 version of the ITF global urban passenger model address travel demand and pollutant emission indicators. They are available for each mFUA, distance bin and subpopulation category. Aggregated indicators such as public transport accessibility, car accessibility, congestion, resilience or average mobility cost are also derived from these results.

The main application of the model is for the biennial ITF Transport Outlook publication[9], providing an overall estimating exercise on the evolution of transport demand and related emissions in the long run[10]. For the sake of simplicity and readability, results are provided for six aggregated modes[11] and eight output regions[12]. Three scenarios are considered in the last ITF Transport Outlook 2021 (ITF, 2021).Recover, Reshape and Reshape+ representing increasingly ambitious efforts to decarbonise the transport sector. Recover is a current trajectory scenario recovering from the 2021 Covid-19 pandemic and sticking to engaged policies. Reshape displays a more ambitious approach to tackling transport CO_2 emissions, while Reshape+ builds on a better and quicker recovery from Covid-19 to improve the Reshape scenario. Examples of results can be found in Figure 4 and Figure 5. These scenarios were established for this publication, but any kind of scenario can be set up in the model. A similar use of the ITF Transport Outlook results at

---

[9] The ITF Transport Outlook serie https://www.oecd-ilibrary.org/transport/itf-transport-outlook_25202367

[10] The model results of the ITF Transport Outlook 2021 can be found on https://stats.oecd.org/.

[11] Private vehicles (private cars, private motorcycles), Paratransit (informal bus, three-wheeler), Public Transit (rail, metro, LRT, BRT, bus), Active and micromobility (walk, bike, scooter sharing, bike sharing), shared vehicle (car sharing, motorcycle sharing), shared mobility (taxi, ride sharing, taxi bus)

[12] Asia, European Economic Area(EEA) and Turkey, Latin America and the Caribbean (LAC), Middle East and North Africa(MENA), OECD Pacific (Japan, South Korea and Australia), SubSaharan Africa (SSA), former USSR (Transition), and the USA and Canada.

a more local scale have been conducted for the European Union and are currently being considered for Asia.

Other outputs of the global urban passenger model include more targeted country or city-level model extractions on regular commercial software and set up for specific analysis. These were recently made to support decarbonising transport projects in Baku, Azerbaijan, and are currently being set up for projects in Morocco, Ulaanbaatar, Mongolia, and Tashkent, Uzbekistan. More punctual result-only extractions are made for preliminary country or city analysis on varied ITF or OECD projects.

Figure 4 ITF Transport Outlook 2021 Evolution of global urban passenger demand in billion passenger-kilometres

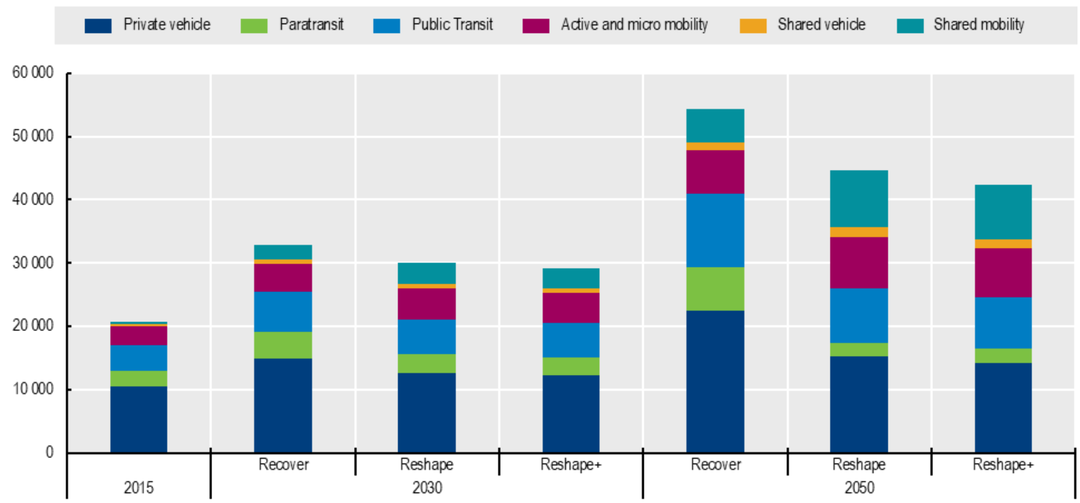
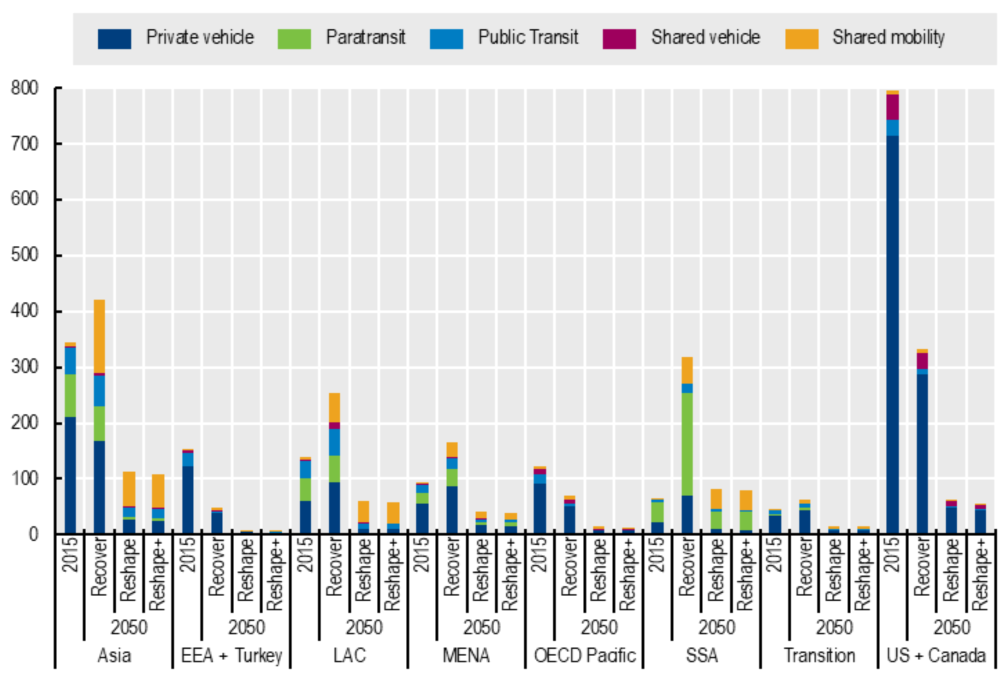


Figure 5 ITF Transport Outlook 2021 Evolution of global urban passenger direct (tank-to-wheel) emissions in million tonnes CO2



6. Policy measure and technology development scenario analysis

In addition to the already useful analysis of urban passenger transport current trends, the model also allows testing the impact of different scenarios on these trends. These global scenarios are made of various policy measures, technology development and exogenous phenomenon levels, which vary by modelling world region. They enable quantifying the impact of each measure individually or coordinated with others on the transport system demand and supply equilibrium and its related emissions. This allows for tracking if the total world transport emissions align with global climate objectives.

Table 3 provides the comprehensive list of 20 measures considered within the 2020 ITF global urban passenger model. These measures can have different levels of disaggregation (e.g. measure impacting load factor can differentiate the private car load factor from the taxi or bus load factor), and or here kept generally aggregated for the sake of readability. The base level of these measures has been calibrated by ITF expertise consensus and by a worldwide survey of about 150 transport experts and decision makers conducted in April-May 2020. Most of these measures come from workshops conducted within the Decarbonising transport in EU initiative and have detailed descriptions with related short literature reviews provided in the ITF Transport Climate Action Directory (TCAD)[13].

Table 3 List of policy measures and technology development accounted for in the model

Measure	Description	Modelling approach
Carbon pricing	Pricing of carbon-based fuels based on the emissions they produce	Increases the cost of all modes based on the related CO2 TTW emissions.
Parking pricing and restrictions	Regulations to control availability and price of parking spaces for motorised vehicles	Increases parking cost and its impact on utilities for the mode choice. Increases the time to access cars and motorcycles. Reduces car ownership.
Road pricing	Charges applied to motorised vehicles for the use of road infrastructure	Increases car and motorcycle costs. Increases the impact of parking cost on utilities for the mode choice. Reduces car ownership.
Bike and Pedestrian infrastructure improvements	Increase in dedicated infrastructure for active mobility	Increases the total length of bike and pedestrian roads. Decreases the time to access a bike. Increases the average speed of active modes. Increases the time to access private motorised modes. Decreases the speed of private motorised modes. Increases the utility of active modes. Increases the share of short trips.
Land-use planning	Densification of cities differentiated between the city centre and the suburbs for cities over 300 000 inhabitants	Increases the population density of the city centre or the suburbs.
Public transport infrastructure improvements	Improvements to public transport network density and size differentiated for cities over and under 1 000 000 inhabitants	Increases metro, light rail transit and bus rapid transit network length. Decreases the waiting time and the time to access public transport modes. Increases the speed of rail, metro, light rail transit and bus rapid transit.

[13] https://www.itf-oecd.org/transport-climate-action-directory-measures

Public transport service improvements	Improvements to public transport service frequency and capacity differentiated for bus and mass transit services	Decreases the waiting time and the time to access public transport and informal transport modes. Increases the public transport and informal transport mode speed.
Integrated public transport ticketing	Integration of public transport ticketing systems	Reduces the fares of public transport modes for tickets and subscriptions. The reduction is stronger for subscription and heavy modes.
Public transport priority and express lanes	Prioritising circulation of public transport vehicles in traffic through signal priority or express lanes	Increases the speed of light rail transit, bus rapid transit, bus, informal bus and informal three-wheelers. Reduces the speed of other road-based motorised modes.
Transit-Oriented Development (TOD)	Increase in mixed-use development in neighbourhoods around public transport hubs	Increases land-use activity mixture. Reduces car ownership. Reduces the disutility elasticity of access time for public transport and informal modes.
Covid-19	Model representation of the Covid-19 pandemic and its medium/long term consequences	Increases the attractivity (utility) of active modes. Decreases the attractivity (utility) of public transport, shared mobility and informal modes.
Autonomous vehicles	Introduction of vehicles with level 5 autonomous capabilities	Decreases the average vehicle fuel consumption and travel distance. Decreases the taxi cost. Increases the speed of road-based motorised modes.
Teleworking	Policies favouring and trends regarding the practice of home office	Decreases total number of trips. Increases the share of short trips under 5 km.
Urban vehicle restriction scheme	Car restriction policies in certain areas and during certain times to limit congestion. Typically applied in the city centre	Decreases the attractivity (utility) of private cars and motorcycles. Reduces the average car speed. Increases the time to access private cars and motorcycles. Decreases car ownership. Increases the number of shared mobility vehicles or stations.
Speed limitations	Traffic calming measure to reduce speed and dominance of motor vehicles through low-speed zones or infrastructure	Decreases the speed of private vehicles, informal and shared motorised modes.
Carpooling policies	Carpooling policies encourage consolidating private vehicle trips with similar origins and destinations	Increases the average load factor.
Vehicle sharing incentives	Incentives to encourage car or motorcycle rental schemes where members have access to a pool of vehicles as needed	Triggers the apparition of these modes of lower GDP per capita thresholds. Increases the vehicle sharing fleet.
Electric and alternative fuel vehicle penetration	Degree of uptake of electric/alternative vehicles in urban vehicle fleet	Triggers the IEA New Policy Scenario (NPS) or the more ambitious Sustainable Development Scenario (SDS). Decreases tank-to-wheel emissions of low energy vehicles.

Mobility as a Service (MaaS) and multimodal travel services	Improved integration between public transport and shared mobility (app integration, as well as physical infrastructure, ticketing and schedule integration)	Increases the number of shared mobility vehicles or stations. Decreases the cost of public transport while increasing the cost of informal and shared modes. Decreases private vehicle ownership. Decreases the impact of the time to access public transport and its attractivity (utility).
Ride sharing and shared mobility	Increased ridership in non-urban road transport differentiated for car and bus-based services	Increases the growth of shared mobility services. Decreases the minimum requirements for the apparition of shared mobility services. Increases the apparition value of mobility service vehicles or stations when coupled with urban vehicle restrictions.

7. Discussion

Modelling the evolution of urban passenger transport systems is key for assisting decision makers in providing evidence-based analysis towards more efficient, sustainable and resilient transport systems reducing social barriers and geographical borders.

This paper has presented the ITF global urban passenger model to discuss the methodology implemented and assess how transport policy measures can shape future travel demand and related emissions. The ITF model is developed under a stock and flow approach. Each city activity is represented by stocks that characterise world urban areas and provide details for each and their city centre. The model relies on in-house development, enabling continuous updates and varied customised applications. Its level of detail for many gender and age population categories, or several distance categories for trips, and the many policy measures and technological developments it enables to test.

These allow an accurate overview of the transport system evolution, translated into pollutant emissions to track transport efforts to reach world climate objectives. To the authors' knowledge, it is the only global urban passenger transport model providing this level of disaggregation and methodology development.

Future developments of the model expected for 2022 will focus on a calibration update with newly available data and an ambition to switch from a market-wide calibration to a country-wide one. They also include further coordination with other ITF in-house models: the ITF global non-urban passenger model completing the overall picture of passenger transport and a recently developed fleet module. This will replace the current exogenous connection with the IEA Momo model to assess transport fleet efficiency.

Along with these in-house developments, the ITF is actively engaged in the Energy Demand changes Induced by Technological and Social innovations (EDITS) research community and is setting up a standardised data communication with the other sectoral models of the community. The ultimate goal is to ease and better understand model interoperability and improve the quality and interpretation of the input and output exchanges between models to assess low energy demand scenarios better.

8. References

Chen, G. and J. Kauppila (2017), "Global urban passenger travel demand and CO2 emissions to 2050: New model", *Transportation Research Record*, , https://doi.org/10.3141/2671-08.

Fulton, L., P. Cazzola and F. Cuenot (2009), "IEA Mobility Model (MoMo) and its use in the ETP 2008", *Energy Policy*, , https://doi.org/10.1016/j.enpol.2009.07.065.

Fulton, L. M. (2018), "Three Revolutions in Urban Passenger Travel", *Joule*, , https://doi.org/10.1016/j.joule.2018.03.005.

ITDP and UCDavis (2021), *The Compact City Scenario – Electrified*, .

ITF (2021), *ITF Transport Outlook 2021* (ITF Transport Outlook), OECD, Paris, https://doi.org/10.1787/16826A30-EN.

Martinez, L. M. and J. M. Viegas (2017), "Assessing the impacts of deploying a shared self-driving urban mobility system: An agent-based model applied to the city of Lisbon, Portugal", *International Journal of Transportation Science and Technology*, June, pp. 1–15, https://doi.org/10.1016/j.ijtst.2017.05.005.

McCollum, D. L., C. Wilson, H. Pettifor, K. Ramea, V. Krey, K. Riahi, … S. Fujisawa (2017), "Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices", *Transportation Research Part D: Transport and Environment*, , https://doi.org/10.1016/j.trd.2016.04.003.

Miskolczi, M., D. Földes, A. Munkácsy and M. Jászberényi (2021), "Urban mobility scenarios until the 2030s", *Sustainable Cities and Society*, , https://doi.org/10.1016/j.scs.2021.103029.

Nordhaus, W. D. and X. Chen (2016), "Global Gridded Geographically Based Economic Data (G-Econ), Version 4", *Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC)*, .

OECD (2020), *Cities in the world: A New Perspective on Urbanisation*, *OECD Urban Studies/European Union*, .

Ortúzar, J. and L. Willumsen (2011), *Modeling Transport*, (3nd Editio)John Wiley and Sons Inc.

Reul, J., T. Grube and D. Stolten (2021), "Urban transportation at an inflection point: An analysis of potential influencing factors", *Transportation Research Part D: Transport and Environment*, , https://doi.org/10.1016/j.trd.2021.102733.

Tikoudis, I., L. Martinez, K. Farrow, C. García Bouyssou, O. Petrik and W. Oueslati (2021), "Ridesharing services and urban transport CO2 emissions: Simulation-based evidence from 247 cities", *Transportation Research Part D: Transport and Environment*, , https://doi.org/10.1016/j.trd.2021.102923.

Trouve, M., G. Lesteven and F. Leurent (2020), "Worldwide Investigation of Private Motorization Dynamics at the Metropolitan Scale", *Transportation Research Procedia*, Vol. 48, https://doi.org/10.1016/j.trpro.2020.08.113.

UN DESA (2019), *World Population Prospects 2019*, United Nations.

WP2 Data deliverable[*]

EDITS[†]

2022-02-28

Abstract

This document describes the progress made in the EDITS Data work package (WP2) in developing the meta database. It contains a general description of the work package aims and goals, and the role that the meta database plays in achieving these goals. The document describes the progress made within 2021 and the foreseen next step in the coming year. The appendix include notes for the EDITS metadata network project (appendix A), and extended text and motivation for this approach. The appendix also includes a hands on worksheet (appendix B) that allows to step by step prepare a description of a data example in the EDITS meta database format.

Contents

1 Introduction **2**

2 EDITS WP2 Data aims and progress **2**

3 Next steps **3**

A Data descriptions **4**
- A.1 Fused descriptions of phenomena, data, and methods 4
- A.2 Planning and executing research on demand phenomena 4
- A.3 Metrology 5
- A.4 Unpacking fused descriptions 6
- A.5 Benefits of data descriptions 6

B Worksheet **7**

C Data description files **10**
- C.1 Classifiers 13

---

[*]do not distribute or cite

[†]Contact Oreane Edelenbosch (o.y.edelenbosch@uu.nl) , Paul Natsuo Kishimoto (kishimot@iiasa.ac.at).

1 Introduction

Comprehensive assessments of sustainability—for instance, the set of targets and measures[1] comprising the Sustainable Development Goals (SDGs), and goals under the UN FCCC—requires research and analysis to address, at once, the entire Earth system and sub-systems within it. The term 'scale' is often used to describe these systems, loosely referring to both *scope*—what is within the boundaries of a focus (sub)system—and *resolution*—the size of the units of observation or analysis: large (coarse) or small (fine).[2]

On the one hand, global-scope analysis is critical because several targets for ecological sustainability are expressed using global measures. In particular, a stable climate is related to the global balance of greenhouse gas sources and sinks, and so the question of whether this criterion is achieved, and how, cannot be resolved with research that addresses only a subset (e.g. by geography, or economic sector) of GHG sources and sinks.

Fine resolution, however, is also important. One reason is that many of the SDGs are expressed in measures related to individuals, households, neighbourhoods, etc.; e.g. that each individual person should have access to clean water. However, even when targets are expressed in measures that are aggregate or global, the systems transformations which take us towards the target values are often and increasingly[3] comprised of actions taken by individuals, households, neighbourhoods, small firms, etc.

Trade-offs naturally arise between scope and resolution: global-scope analysis with individual humans as units of analysis adds also uncertainty and complexity, where adding more details increases the number of uncertain assumptions that have to be made, and results in reduced transparency. However, certain phenomena such as social transitions, that can be triggered by an interplay between policy, contextual changes, different actors that exchange information, knowledge and preferences, might not be able to be described well without these detailed elements.

These examples illustrate that different tools of analysis are needed to be able to describe different parts of the system. Some that have a more narrow scope and some with a more broad overarching view. Importantly, to be able to communicate between these different tools, there should be a common language. This is also important, given the diversity of backgrounds and disciplines that are involved in the sustainability science research, and that are also part of the EDITS community. Therefore the first step, is to be able to communicate in a transparent and consistent way what data we have, know about, possibly can share.

2 EDITS WP2 Data aims and progress

There are two overarching aims and goals of the EDITS data working group:

- Consistent and transparent data communication between the diverse groups that are involved in EDITS but can also be used by the broader sustain-

[1] Sometimes 'indicators'.
[2] The term 'granularity' is sometimes used.
[3] Even, from the equity perspective—*necessarily*.

able science community, to allow collaboration, learning from each other, enriching low energy demand analysis.

- Identify the most critical data gaps that need to be overcome to strengthen the description of LED pathways. This is done by identifying first data needs and second data availability.

Contributing to the first aim of the EDITS data working group, in 2021 this working group has focused on developing a metadata repository which allows to communicate in a consistent and transparent manner about available data. To do so a repository has been created on Github: https://github.com/iiasa/edits-data. This repository provides a simple example of how to communicate about data, and allows users also to learn to do so. The metadata repository comes with clear instructions that can be found in the appendix of this report. First appendix A discusses provides the background of why this is relevant, following with appendix B that consist of a set of questions to first unpack their data and be able describe it. Finally, in appendix C a simple, easy accessible text-based file can be found, in which these descriptions can be captured and shared with the community when uploaded to the repository.

3 Next steps

The metadata repository has been tested by a few members of the EDITS community. So far those that have worked with the repository and worksheet were positive, emphasizing that thinking about what data they have, and learning how to communicate clearly is very useful. There have been comments during the EDITS project meeting that for people that are not familiar with working with python or github that this might be a barrier. To fill the data repository only limited programming skills are required as the information is collected through simple text files. In the next year the aim would be to involve and encourage more EDITS members, and possibly beyond, to describe available data in the developed meta repository. A suggestion was made to organise workshops or instruction videos to explain the process, which this working group aims to take up.

A Data descriptions

A.1 Fused descriptions of phenomena, data, and methods

In discussing real-world phenomena,[4] modelers[5] often give *fused descriptions* that combine information about:

- the particular *phenomena* that are represented by the model (e.g. "electric vehicle (EV) adoption"),
- the specific numerical or modeling *methods* used to represent the phenomenon (e.g. "a logit [sub]model", "optimization"),
- *structure and attributes of data* used at different stages of a modeling workflow, including:
  - input ('upstream', 'calibration') data obtained from other sources,
  - the data ('variables', 'endogenous' quantities, 'parameters') directly occurring in the core methods or equations,
  - output ('derived', 'reported') data that are calculated using the results of the core methods.

In some contexts, these fused descriptions are entirely appropriate and useful: they identify items that differ across models and methods used by researchers in that specific (sub)-field or community. At the same time, they avoid verbose restatement of things that *do not* vary.

For example, consider a community of researchers studying (a) transportation (b) on roads (c) in privately-owned, light-duty vehicles (d) in global spatial scope and (e) a climate-policy-relevant temporal scope, e.g. to 2050 or 2010. These researchers might commonly work with input/model/output data that:

- has global spatial scope, and spatial resolution of individual countries, and
- has temporal resolution of years or multi-year periods.

Within this community, to restate these points (or (b) and (c)) is often unnecessary, and to omit them makes for clearer communication.

A.2 Planning and executing research on demand phenomena

Among other goals, the EDITS project aims to identify and facilitate a "model complementarity project" (MCP), focused around possibilities for dramatic transformation of demands for energy services. This is a research activity that deliberately crosses sub-field/-discipline boundaries, and explicitly aims to make connections between models at that represent the same phenomena, at very

[4]In EDITS these are phenomena that may affect the amount or nature of activities that give rise to energy demand

[5] Here we include individuals and groups that build and/or operate (a) integrated assessment models, (b) large-scale, global, or (herein) *macro* models, or (c) fine-resolution models, often with narrow scope.

different scopes and resolutions.[6] In this context, the shared assumptions and implied information omitted from within-field fused descriptions *are not fixed*, and to omit them is no longer proper.

Fused descriptions, in fact, obscure the relative difficulty of connecting different pairs of models. This necessitates work to investigate every candidate pair and answer questions like:

1. Do these models both treat (respectively, output and input) data that measures something related to the phenomenon of interest?
2. Is this the *same* concept or measure?
3. Is the "coverage" (spatial and temporal scope and resolution) aligned? If not, what methods, assumptions, or additional data are required to translate the data?
4. Are other dimensions of the data aligned in scope and resolution?

This work is frequently repeated, creating a needless inefficiency in research.

A.3 Metrology

A little up-front effort in rudimentary metrology can substantially reduce this duplicated work. By *metrology* we refer to the explicit discussion of what is measured, and what those measurements (i.e. data) comprise: the background and systematized concepts, specific operationalized measures, the measurement methods, units, resolution, scope, and other attributes of data.[7]

With clear metrological descriptions of the data used to research particular phenomena, the work to achieve particular model–model connections—sometimes trivial, sometimes significant and challenging—is revealed by inspection, instead of through listing out (again: repeatedly but needlessly) the implicit details omitted by fused descriptions.

For example, suppose:

- Model/Source A provides transport vehicle activity data with a certain spatio-temporal scope, spatial resolution of countries, additional dimensions, etc., in units of billions of vehicle-miles per year.
- Model B requires vehicle activity data with the same spatio-temporal scope, additional dimension, etc.—except in units of million vehicle-kilometres per year, and at spatial resolution of world-regions comprising multiple countries each.
- Model C requires vehicle activity data (the *same* measure), but with spatial resolution of individual cities within a country, and temporal resolution that separates peak- from off-peak commuting hours.

[6] See note 5 above. The idea is that fine-resolution models (or model-based research) focused on the nuances of these phenomena provide data or stylized facts that can be used to improve global/macro/long-term models.

[7] For an overview and the ways inattention to metrology can threaten validity of research, see **adcock-collier-2001**.

Fused descriptions (C: "Our model requires vehicle activity data" / A: "Our model outputs vehicle activity data!") do not help identify that, while connecting A to B is trivial (unit conversion and aggregation, both simple operations), connecting A to C will require substantial work.

This type of evaluation is necessary to identify which model–model connections are feasible with given research resources and objectives. When this evaluation is costly *per se*, the selection of connections will be more ad-hoc than systematic; there is a disincentive to try new connections or pursue reproduction; and difficulties in connecting e.g. A to C will come as a surprise.

A.4 Unpacking fused descriptions

We provide:

- a process/set of questions (the worksheet in Appendix B) that EDITS modelers and researchers can answer about their data (both model-based and from other sources) to unpack fused descriptions into complete metrological descriptions,
- a simple, text-based file format—easily authored, versioned, and exchanged—to capture these descriptions (see Appendix C),
- tooling to collect, collate and filter these descriptions, as an aid to identifying possible model–model connections and their relative difficulty.

A.5 Benefits of data descriptions

Descriptions, prepared once, can then be re-used for a variety of purposes indefinitely. This reduces the need to prepare, fill out, and collate new surveys for new MCPs and "model intercomparison projects" (MIPs). EDITS focuses on phenomena related to demand transformations, but the same metrological descriptions can be examined to judge the suitability of models/data for other research questions.

The file format we suggest is deliberately as simple as possible. This is intended to reduce barriers to entry for researchers more accustomed providing fused descriptions of data, e.g. in the text of research papers or reports. However, because the format uses a popular markup language (YAML) and is machine-readable, descriptions prepared per the process here can later be *automatically* transformed to more sophisticated formats established by standards such as SDMX (ISO 17369:2013; see https://sdmx.org). This makes model metadata, and to some extent the actual data, intelligible to a wider variety of existing tools and users.

Descriptions need not be complete. That is, modelers do not need to enumerate *all* input/output data for their models in order to facilitate identification of model–model connections; only a subset.

B Worksheet

First—these questions **do not** ask about:

- *phenomena*—the real-world dynamics that are represented by or studied with your model or data set.
- *methods*—how the phenomena are represented in your model.

Those things are, of course, always present. These questions, however, help promote and develop facility with explicit metrological thinking. This is often skipped, but is critical to identifying *whether* your model/data set can be connected with others to study such phenomena, and *how easy or hard* such connections are.

1. Choose a single *'kind' of data* related to your model/data set. We will refer to this a **quantity**.

   To begin with, any selection is fine. Later, EDITS participants will identify certain concepts or measures (Q3, below) related to energy demand phenomena of interest; then start with those before treating others.

2. What are the **units of measurement** for this quantity?

   Example: kilometres.

   If there are 2 or more units of measurement, then in Q1 you selected multiple quantities, not a single one. Narrow your selection.

3. What is the **concept** or thing measured (the **measure**)? In other words, what does each datum (single data point or observation) of this quantity count or measure?

   Answer this question in two ways:

   (a) What is the *background (general) concept*?

   (b) What is the specific way that concept is *systematized*?

   Example 1: Passenger transport activity, systematized as the total distance travelled by all people from a geographical region, in a period of time.

   Example 2: Passenger transport activity, systematized as the total number of trips made by all people from a geographical region, in a period of time.

   Note that:

   - Example answer 1 distinguishes what is measured (distance) from the units used to express particular measurements (e.g. kilometres, as in Q2).
   - Example answers 1 and 2 give the same background concept (Q3a), but it is systematized differently (Q3b).
   - You may have 2 or more quantities that use the same measure, but with different dimensions, scope, etc. Don't worry about this for now.

4. What **dimensions** do the data have?

   There are some ways to go about answering this question.

   - One way is to imagine your data in a "long" table, with one datum ('value', 'observation') per row. Then each other column corresponds to a dimension.
   - If you have a mathematical formulation (A_{xyz}) or code, the dimensions may be stated explicitly (x, y, z).

   In most cases, your data will have *time* and *space* dimensions. These are sometimes given different names, like 'year', 'date', or 'period'; or 'country', 'region', 'city', or 'node'. We use the names 'time' and 'space' for commonality; the questions below capture other information implied by these names.

   Example: for transport vehicle activity data, dimensions may be: time, space, technology (of the vehicle powertrain), type of transport service provided.

5. Choose just one dimension. What is the underlying **concept**?

   Just like the actual measurements/values (Q3), each dimension encodes a general background concept, systematized in a certain way. It may be easier to return and answer this question after answering the ones below.

   Example: in the example from Q4, the "technology" dimension refers to the concept of "the transport vehicle's powertrain technology," as opposed to things like whether the vehicle is automated using self-driving 'technology'.

6. For this dimension/concept, how is it **operationalized**?

   For some dimensions (often time and space) this question has the same answer as "What is the **resolution** along this dimension?"[8]

   Example 1: vehicle power-train technology dimension may be operationalized as one of 3 discrete values: "Electric," "Internal combustion," or "Hydrogen fuel cell."

   Example 2: space may be operationalized as specific countries, labeled by their ISO 3166 alpha-3 codes.

   Just like the difference between background concepts and systematized measures (Q3a vs. Q3b), there can many valid ways to operationalize (this Q) a concept used as a data dimension (Q5). Don't worry about other ways of doing it; describe how it is done in your data in particular.

   Be sure to give (or reference) specific definitions for discrete values, if you know that those definitions vary. For example, you can state that the discrete label "2025" is used for a time dimension, but be specific about whether this is "a single year (e.g. 2025)" or "a 5-year period, of which the label is the first year (e.g. 2025-01-01 to 2029-12-31)" or something else.

[8] A fused description might say: "we have/use this data *at the level of* individual countries/cities. . . " or similar.

7. For this dimension/concept, what is the **scope**?

   You may have already answered this in your response to Q6.

   Example: a 'material' dimension (for a measure of "mass of material required to produce the artifacts, e.g. transport vehicles") might be operationalized (Q6) as one of the 2 discrete values, "steel" or "aluminum".

   In this case, the scope might be "Only the materials listed." This explicitly excludes other materials such as copper or cement.

8. Repeat Q5 through Q7 for all other dimensions.

9. You now have a complete description one **quantity**. This comprises:

   - The **measure**.
   - The **dimensions**, as well as the way these dimensions concepts have been operationalized (**scope** and **resolution** for each).
   - Other nominal information, including the **units** of measurement.

   Is there anything else about the structure of this data quantity that is not captured so far?

10. Repeat Q1 through Q9 for other kinds of data.

C Data description files

This appendix describes a format for files containing data descriptions.[9]

The format is based on YAML, a simple and popular text markup language. This is to make it as accessible as possible to researchers—low work in understanding the format and low overhead in data entry—while remaining machine-readable.

Below, highlighted snippets of YAML appear, surrounded by plain-text description of what information they contain and how to prepare them.

General points:

- At the top level of the file, the main sections (like `title:`, `description:`, `measure:`, `dimension:`, etc.) can appear in *any* order.
- Do not use fields or sections aside from the ones described here.
- The EDITS demo code can check your YAML syntax and the file format. See the README.

Format version.

```
version: 1
```

The format may be revised. This indicates which version is used in the current file.

General information.

```
title: Example data description
description: |-
  This is an example data description for the EDITS project. This
  description field can be used for free-form information about
  the data set/database/model described in the current file.
```

The `description`...

- is the place to put any reference to a URL or publication (give the DOI URL, e.g. `https://doi.org/10.1234/example.journal.5678`) containing more detailed information.
- Can be formatted as a wrapped, multi-line YAML string, as indicated by the "`|-`" characters after the colon. See `https://yaml-multiline.info/`

Classifiers. These are tags or labels for nominal/qualitative information about the entire data set/database described in the file. They are loosely structured, hierarchical, with double colons (`::`) separating parts.

```
classifiers:
- "Availability :: Public"
- "Kind :: Model input"
- "Sector :: Transport"
```

The section uses YAML list syntax: each list element is prefixed by a hyphen and space (`- `). It is recommended to enclose the entries in double quotes.

[9]This is the format understood by the code at `https://github.com/iiasa/edits-data` that collects and collates descriptions.

Data provider. This section contains information on the person providing the data. For instance, if the classifiers indicate the data is for collaborators only, this is the person or persons to contact about such collaboration.

```yaml
provider:
  organisation:
    International Institute for Applied Systems Analysis (IIASA)
  contact: kishimot@iiasa.ac.at
```

Both sub-fields, `organization:` and `contact:`, are free-form. It's recommended to include at least a name and e-mail address. The section uses YAML "mapping" syntax, e.g. each sub-field is indented (by 2 spaces), then followed by a comma, a space, and the entry text.

Measures. This section contains the answers to Q3a and Q3b. It uses YAML mapping syntax.

```yaml
measure:
  population:
    description: Count of people in a given area or category.
  disutility cost:
    description: >-
      Monetary equivalent to the intangible/non-monetary disutility
      ('inconvenience', etc.) that a person has towards using a
      specific technology; separate from the real, monetary costs
      of obtaining or using that technology.
```

Here, "population" and "disutility cost" are short IDs for the concepts/measures, to be referenced in the `quantity:` section, below. Notice they are indented the same amount. Within each, there is a further mapping, with just one field, `description:`. As with the top-level description, this can be a mapped multi-line string.

Again: be specific! If "population" or "stock" might have multiple different meanings across EDITS disciplines, this is the place to describe what it means in the data described by the current file.

For this section, as well as the dimensions and quantities (below), you can give an empty mapping ({}) as a placeholder:

```yaml
measure: {}
```

Dimensions. This section contains the answers to Q5, Q6, and Q7. Each dimension concept should appear once, and may be referenced by multiple quantities (below).

```yaml
dimension:
  time:
    scope: historical (1990-2020) to 2100
    resolution: 5- or 10-year periods, or annual
    description: Data at <5 year resolution can be aggregated.
  space:
    scope: global
```

```yaml
    resolution: country or R11 regions
    description: Data at the country resolution can be aggregated.
  census_division:
    scope: Continental United States
    resolution: 9 census regions, or total
    description: >-
      Census divisions of the United States. This is used to map
      data from US-TIMES and MA³T.
```

Each entry has exactly/only the following fields:

`scope:` contains the answer to Q7.

`resolution:` contains the answer to Q6.

`description:` contains all other information about the background and systematized concept, usage. Like the top-level description, you can exclude external references, e.g. if there is a long list of codes that don't need to be replaced in the file.

Quantities. This section contains the answers to Q1, Q2, Q4, and Q9. It is a YAML list, with one entry per distinct quantity (Q1).

```yaml
quantity:
- measure: population
  dimensions: [time, space, consumer_group]
  units: persons
  description: >-
    With these dimensions, this data captures the "shares" or
    division of the total population across the consumer groups.
- measure: disutility cost
  dimensions: [time, space, technology, consumer_group]
  units: USD_2015
  description: >-
    These data only cover the 12 `technology` labels associated
    with the LDV `mode`.
```

Each entry/quantity is described with the following fields only:

`measure:` A reference to one of the measures appearing in the `measure:` section of the file. The same measure may be referenced by multiple quantities, with different meaning or dimensions.

`dimensions:` A list (enclosed in `[]`) of dimensions appearing in the `dimension:` section of the file.

`units:` Units of measurement (Q2).

`description:` Further description of the quantity, including:

- the meaning of the dimension concepts with respect to this quantity/measure.

- any details of data coverage or construction; e.g. if only some labels along one of the dimensions are included.
- for data classfied as `Kind :: Model input`, alternate forms of data that would also be usable.

C.1 Classifiers

These are a recommended set of values to use in the `classifiers:` section of a data description file.

Data availability. This describes any terms on which the data is provided to be used by others.

`Availability :: Public` Data is provided publicly, free of charge.

`Availability :: Registration required` Data is provided free of charge, but users must give some contact information or agree to some terms. The `description:` field should describe what these are and where to register.

`Availability :: Collaborators only` Data is only provided to collaborators in specific research projects. The `description:` field should elaborate.

`Availability :: Proprietary/commercial` Data is only provided to paying customers.

Kind of data.

`Kind :: Model input` Data required by a particular model as input or for calibration

`Kind :: Model output` Output from a particular model.

`Kind :: Model core` Data used in the core methods of a particular model as part of its representation of certain phenomena (including demand).

`Kind :: Official statistics` Published by 1 or more official statistical bodies.

Please create new classifiers under `Kind ::` as appropriate. This list will be expanded as we see them in the EDITS network.

DINÂMIA'CET

CO-BENEFITS OF DIGITAL CONVERGENCE AND SHARING OF CONSUMER GOODS TO REDUCE CARBON EMISSIONS AND PROVIDE DECENT LIVING STANDARDS

Nuno Bento
University Institute of Lisbon (ISCTE-IUL)
DINÂMIA'CET-Iscte, Lisbon, Portugal

25/2/2022

dinamia'cet _iscte

Centro de Estudos sobre a Mudança
Socioeconómica e o Território

Co-benefits of digital convergence and sharing of consumer goods to reduce carbon emissions and provide decent living standards

Nuno Bento

University Institute of Lisbon (ISCTE-IUL), DINÂMIA'CET-Iscte, Lisbon, Portugal

Abstract

Access to modern energy services (entertainment, food preparation, hygiene, communication, etc.) that are provided by consumer goods remains highly inequal; at the same time, the growing adoption of consumer goods due to rising incomes in Global South is having implications in energy demand. There are growing signs that the current model of organization of production and consumption of these energy services is too costly and environmentally inefficient, and therefore should evolve. New social and technological innovations, enabled by growing digitalization, emerge that can help addressing the unsustainable trends in consumer goods. This research focuses on the potential of two innovations (digital convergence and sharing economies) to provide a more affordable, energy efficient, access to consumer goods. It simulates the effect of the dissemination of digital convergent technologies and sharing of consumer goods in material consumption and energy demand in a way that ensures decent living standards for all and limits global warming to 1.5ºC. For that, we use a highly granular bottom-up representation of consumer goods. The results show that digital convergence and sharing can reduce the costs of consumer goods and ensure decent living standards. They can also limit the increase in the number of appliances to 135% and lower the energy demand in 28% between 2020 and 2050. These results demonstrate that providing decent living standards for all humanity is compatible with the efforts to mitigate climate change and open new perspectives for the mitigation in other sectors.

Outline

1. Current service provision is too costly, energy inefficient and emission intensive…………………4

2. A changing context: emergent trends in digital innovations…………………………………………….6

3. A scenario with digital convergence and sharing…………………………………………………………..7

4. Social gains with environmental co-benefits…………………………………………………………………11

References……..13

Supplementary Information………………………………………………………………………………………….15

Figures

Figure 1. Number of devices needed to ensure Decent Living Standards (DLS) by regions of the Global South, in millions……………………………………………………………………………………………………8

Figure 2. Effects of digital convergence and sharing in the number of appliances (left) and in the energy demand from appliances (right) in 2050…………………………………………………………………9

Figure 3. Social gains……………………………………………………………………………………………………..11

Tables

Table 1. Decent living standards assumptions……………………………………………………………………10

Table 2. Inputs for simulating the effects of digital convergence and sharing devices…………….10

1. CURRENT SERVICE PROVISION IS TOO COSTLY, ENERGY INEFFICIENT AND EMISSION INTENSIVE

Several aspects concur to the problematic organization of the production and use of consumer goods[1] today. Access remains extremely unequal to basic appliances that provide modern energy services such as television entertainment, food and medicines refrigeration or machine-wash of laundry (Oswald et al., 2020). Data on penetration and ownership of household appliances is generally lacking, especially for the Global South (Cabeza et al., 2018). However, recent estimates, based on a compilation of national surveys, suggest average ownership rates in Africa for TVs (17), fridges (10) and washing machines (2), that are too low comparing with respectively 98, 95 and 92 in the Global North (Poblete-Cazenave et al., 2021). Attaining universal access to modern energy services by 2030 (UN SGD 7) will be challenging for several reasons. Already over 700 million people still lacks access to reliable electricity, particularly in Central and Southern Asia as well as Sub-Saharan Africa (ESMAP, 2022).

Prices of appliances remain high for a large population in low-income countries. Income is still an important determinant for the acquisition of energy-using assets (Gertler et al., 2016). However, the prices of household appliances are declining over time. For example, they have reduced in average 20% in the last 25 years in the European Union (Eurostat, 2022). Despite the increase in income and the reduction in prices of the appliances in the past decade, a large share of the population in the Global South cannot still afford the access to modern services provided by consumer goods. For example, a household in India faces higher prices of TVs, frigdes and washing machines in terms of purchasing power parity (PPP) than in Brazil or South Africa (Rao & Ummel, 2017). Higher revenues per capita in the Global South in 2050 (expected to roughly double in the “middle of the road” IPCC SSP2 scenario) are still not enough to provide universal access (Poblete-Cazenave et al., 2021).

Efficiency improvement rates in consumer goods have generally slowed down in the past decade. Efficiency gains in major appliances has stabilized since 2014 (Enerdata, 2020). On the other hand, the number of smaller devices has increased twice as fast as for major appliances since 2010 (IEA, 2021). Even though small consumer electronic appliances (e.g., tablets or

[1] Consumer goods are by definition products that consumers buy to perform one or several services (lighting, cooking, entertainment, etc.) for their own (direct) use, as opposed to capital goods that are mainly used in business. They can include all sort of plug-loads in buildings that are not fixed and dedicated to thermal comfort. Large and small household appliances, such as refrigerators and radio alarm clocks respectively, are a major group of consumer goods. For this reason, in the rest of this paper, we will be referring to these goods interchangeably as consumer goods, appliances, equipment or devices.

smartphones) have low energy consumptions, they have relatively higher requirements in manufacturing (i.e., higher embodied energy) (ADEME, 2019).

Emissions from appliances use are rising fast, threatening the efforts of climate mitigation. Appliances are among the fastest growing categories of energy demand, driven by increase in revenues and rising ownership of devices (IEA, 2021). They already account for 15% of global final electricity demand, or one-third of the energy consumed in buildings if lighting and cooking are included (IEA, 2017). If demand keeps increasing at the same pace, overrunning the improvements in energy efficiency, one out of six units of final energy demand in 2050 will go to consumer goods (i.e., appliances and electric plug-loads), even in a low energy demand scenario (Grubler et al., 2018). On the one hand, income growth can have nonlinear effects on energy demand in developing countries (Getler et al., 2016). On the other hand, demand for some services such as cooling may also increase because of global warming with impacts on energy consumption (Khosla et al., 2020). This would put at risk the efforts to reduce the energy consumption in buildings, which already account for 60% of global electricity demand, corresponding to 28% of global energy-related CO2 emissions in 2019 (IEA, 2020). The pandemic could attenuate or reinforce this increase in electricity demand depending on whether the recovery will lead to a more intensive utilization of appliances or to the duplication of residential and non-residential space (Kikstra et al., 2021).

Therefore, there is the need to identify better alternatives to modernize the provision of energy services with appliances that are more accessible, efficient, and cleaner. Previous research has focused on quantifying energy requirements from normatively defined services (e.g., Millward-Hopkins et al., 2020; Rao & Ummel, 2017). More recent works estimate changes in the access to energy services driven by rising incomes that explicitly differentiates by end uses and regions (Poblete-Cazenave et al., 2021). However, these analyses assume no technological change in 2050. There is no investigation on the contribution of new technologies like those that perform multiple services (e.g., television and internet access through computer replaced by smartphones) or serve multiple people (e.g., heat, ventilation and air conditioning systems shared in buildings instead of owned separately) that can have important implications for improving access to modern services and lowering energy demands.

Therefore, this investigation addresses the question: How could improve the provision of modern energy services associated to consumer goods to provide decent living standards and meet climate goals? The work specifically estimates the effect of new digital consumer goods innovations in a highly granular bottom-up representation of appliances. This is used to simulate the changes in energy demand under a scenario which ensures decent living standards for all and limits global warming to 1.5ºC. The research opens new perspectives to address the United Nations' Sustainable Development Goal 7 on universal access to affordable, reliable, and modern energy services for all by 2030. It particularly demonstrates that providing decent living standards for all humanity is compatible with the efforts to mitigate climate change. This result is in line with an emerging literature that shows evidence of positive effects of demand-side solutions in well-being (e.g., Creutzig et al., 2022).

2. A CHANGING CONTEXT: EMERGENT TRENDS IN DIGITAL INNOVATIONS

New business models are emerging based on technological and social innovations, the most often digitally enabled, that can change the way that goods and services are provided. Two trends are particularly promising to revolutionize the production and use of consumer goods which provide important energy services (e.g. communication, entertainment, productivity): digital convergence and sharing economies.

Digital convergence refers to the tendency of stand-alone objects to converge onto new devices, creating "multifunctional" objects that execute multiple services. The typical example is the smartphone that converged previously unrelated technologies such as the telephone, television, and computer through an increasing interplay of shared parts consisting of digital electronics and software including applications or "Apps". Smartphones can substitute at least seventeen devices, from alarm clock to GPSs and radios, with thirty times less power in use and hundred times less power in standby (Grubler et al., 2018). Already the mobile phone (feature phone) knew unprecedent speed of diffusion, becoming the most democratic technology in less than two decades (Bento, 2016). These highly efficient devices have provided not only communication (oral and text messaging), but also other types of services such as access to financial services in developing context.

Sharing economy, as opposed to individual ownership, denotes the case in which multiple people use an otherwise underutilized good or service, such as cars, homes or devices. Ridesharing (through platforms running on "apps") has displaced the sales of roughly 2 million cars in 2016 in the world, with particular impact in China (960 thousands) and India (540 thousands) (Statista, 2022). Collective living or working improves the possibility that people share more amenities such as lighting, space heating/cooling, living spaces, and appliances. Previous research shows evidence that collective living reduces emissions in average 0.3 tCO_2eq/cap per year (Ivanova et al., 2020). Finally, several devices are increasingly shared at the buildings or community levels. For example, shared washing machine rooms are frequent in multifamily buildings in North America and increasingly so in Europe and in other parts of the world. Shared devices can run more efficiently at the lowest energy consumption and operational cost (Ivanova et al., 2020). By lowering the number of devices through their collective use, sharing has the potential to reduce the embodied energy associated to the avoidable goods, as well. Therefore, moving from owning to sharing presents several benefits such as more intensive use of the good or service, waste minimizing (circular economy) and reduction in the material needs (dematerialization).

Sharing economy and digital convergence can contribute to significantly lower the number of consumer goods for the same needs. They open promising avenues to lower both the energy demand and the material consumption from appliances. More importantly, digital convergence and sharing could lower the cost of the service, enabling the widespread access to the modern services provided by consumer goods (entertainment, communication, lighting, etc.), particularly to the population in developing countries where their access is more limited today.

3. A SCENARIO WITH DIGITAL CONVERGENCE AND SHARING

How a scenario with digital convergence and sharing in consumer goods would look like? We simulate the effects of digital convergence and sharing in promoting the widespread access to consumer goods and reducing energy demand. The analysis departs from the Low Energy Demand (LED) scenario (Grubler et al., 2018), an influential and highly detailed scenario for decarbonization, including an explicit representation of consumer goods. We updated the estimates for the stock of appliances in 2020 with real data and by considering a larger number of devices. We also adjusted the projections for the number of appliances in 2050 by calibrating with the differences in the revenue per capita between 11 regions. Hence, we estimate that the number of appliances will grow to 191 billion devices in 2050 (+177% than in 2020). These appliances would use 12,738 TWh, assuming similar trends of energy improvement as in the original LED scenario.

We estimate the number of devices needed to provide decent living standards (DLS) for all based on the assumptions in Tables 1-2. This would require 8 billion devices in addition to the base estimate for 2050, distributed among the Global South regions as shown in Figure 1.[2] The

[2] See the S.I. for a detailed account of all the calculations, assumptions and data sources.

most needed appliances are for food preparation (stoves, oven) and thermal comfort (portable air conditioner). The regions with the highest needs are Sub-Saharan Africa (SSA), South Asia (SAS), and Latin America and the Caribbean (LAM).

Figure 1. Number of devices needed to ensure Decent Living Standards (DLS) by regions of the Global South, in millions. Regions include Sub-Saharan Africa (SSA), Centrally Planned Asia and China (CPA), Latin America and the Caribbean (LAM), Middle East and North Africa (MEA), Other Pacific Asia (PAS), and South Asia (SAS).

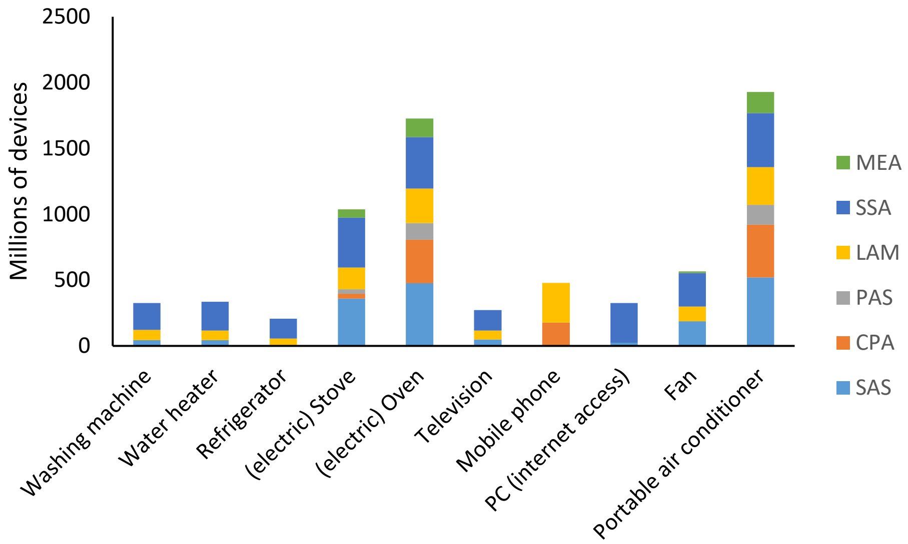
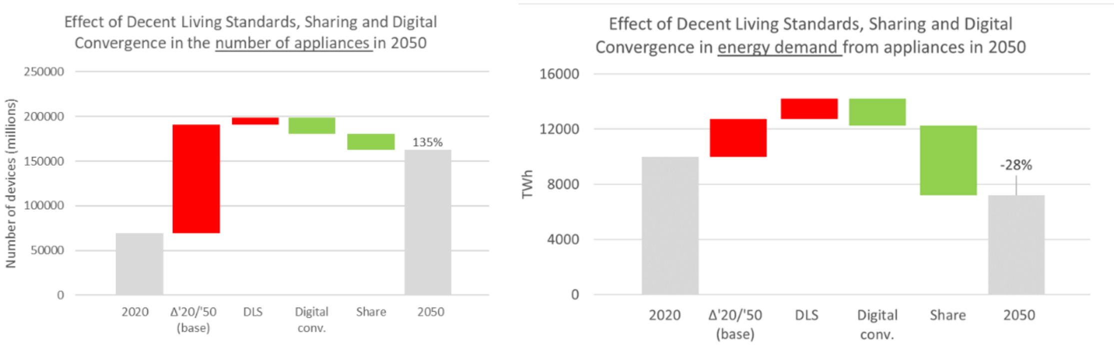


Figure 2 shows the effects of digital convergence and sharing in the number of appliances and energy demand. Digital convergence of devices reduces the global number of devices in such a way that more than compensates the impact of providing enough energy services (lighting, communication, etc.) to ensure decent living standards for all in 2050 (Figure 2, left-hand). Digital convergence also partially mitigates the estimated growth in the number of devices from 2020 to 2050. On the other hand, sharing further reduces the number of devices in use in 2050. Therefore, digital convergence and sharing limit the growth in the number of devices to 135%, instead of tripling the number of 2020 (200%) in the base growth with DLS.

Figure 2. Effects of digital convergence and sharing in the number of appliances (left) and in the energy demand from appliances (right) in 2050



Sharing devices has the double of the effect of digital convergence in lowering the energy demand (Figure 2, right-hand). Sharing, instead of owning devices such as washing machines and electric ovens, increases several times the efficiency in the provision of services such as laundry washing or food preparation. In fact, despite of their higher energy intensity (assumed to double, at least), shared devices replace several single-owned objects. In so doing, sharing has a greater effect than digital convergence in reducing the energy demand to provide the same level of energy services. Overall, sharing and digital convergence allows that a higher number of devices in operation in 2050 use 28% less energy than in 2020.

Sharing and digital convergence reduce the material needs of consumer goods.[3] Comparing with the base case, they lower 35% to 32 million tons the annual replacement flux in 2050, and 39% of the embodied energy to 2,724 TJ. Further solutions can reduce the material requirements of consumer goods even more. The extension of the average lifetime in 25% (i.e., one extra year every fourth year of lifetime) would reduce 48% the annual replacement flux (13 percentual points), ceteris paribus. Similarly, reducing further one third the weight of devices lowers 54% (roughly 20 percentual points) the annual replacement flux in 2050. These possible solutions could amplify the benefits of digital convergence and sharing in lowering both the carbon emissions and the costs of the devices.

[3] See the S.I. for the analysis on the impacts on material consumption.

Table 1. Decent living standards assumptions

Category	Appliance	Service	Unit	2050 ownership per 100 HH	Source
Lighting	Lamps	2500	lumens/house	400	Millward-Hopkins et al., 2020
Hygiene	Washing machine	80	kg washing/year	100	Millward-Hopkins et al., 2020
	Water heater	20	liters/cap/day	100	Millward-Hopkins et al., 2020
Food preparation	Refrigerator	1	fridge-freezer (cooling)	100	Millward-Hopkins et al., 2020
	Electric Stove	1	stove (heat)	100	Hypothesis
	Electric oven	1	oven (heat)	100	Hypothesis
Communication	Television	1	TV (entertainment)	100	Rao & Ummel, 2017; Rao et al., 2019
	Mobile phone	1	phone person over 10 years old	300	Millward-Hopkins et al., 2020
	PC (internet access)	1	laptop (productive/ent./com.)	100	Millward-Hopkins et al., 2020
Thermal demand	Fan	15	m2/cap (cooling)	100	Millward-Hopkins et al., 2020
	Portable AC	15	m2/cap (cooling/heating)	100	Millward-Hopkins et al., 2020
Miscellaneous	Miscellaneous				

* can run on gas in 2020. Assumed a mean household size of 4 persons and a mean house size of 60m2.

Table 2. Inputs for simulating the effects of digital convergence and sharing devices

Sector	Category	Appliance	Type	Sharing house-holds	Sharing level	Digital convergent devices per 100 Households	Energy intensity	Notes
Residential	Lighting	Lamps	sharing	10	age		double	(a)
	Hygiene	Washing machine	sharing	10-100	building, age, urbanization		double	(b)
		Water heater	sharing	10	age, building		double	(c)
	Food preparation	Refrigerator	sharing	10	age		double	(a)
		Freezer	sharing	10	age		double	(a)
		Electric stove	sharing	10	age		double	(a)
		Electric oven	sharing	10	age		double	(a)
	Thermal demand	Portable air conditioner	sharing	10	building		double	(d)
	Communication	Television	digital conv.			0	unchanged	(e)
		Mobile phone	digital conv.			100	unchanged	(f)
		PC (internet access)	digital conv.			0	unchanged	(e)
	Miscellaneous	Misc electric loads	digital conv.			33	unchanged	(g)
Commercial	Hygiene	Water heater	sharing	10	building		unchanged	(h)
	Thermal demand	Portable air conditioner	sharing	10	building		unchanged	(h)
	Communication	Television	digital conv.			0	unchanged	(e)
		PC (internet access)	digital conv.			100	unchanged	(i)

(a) A third of the population under 30 years and over 65 years share houses with 10 households in average.
(b) Half of the urban population served by laundry shops (1 machine per 100 households); people living in multifamily buildings in urban areas and co-living (elderly, young, etc.) share laundry room (1 machine per 10 households).
(c) Shared in co-living houses (elderly, young, etc.) and at the building level in average by 10 households.
(d) Shared at building level.
(e) Converge into an "all-in-one" media portable device.
(f) One per capita. Standby energy reduction compensates for increase in energy intensity (kWh/year).
(g) Digital convergence divides by three the number of electric loads.
(h) Shared at commercial building level.
(i) Become "all-in-one" media converging device. Efficiency improvements and standby consumption reduction compensate the effect of high load factor.

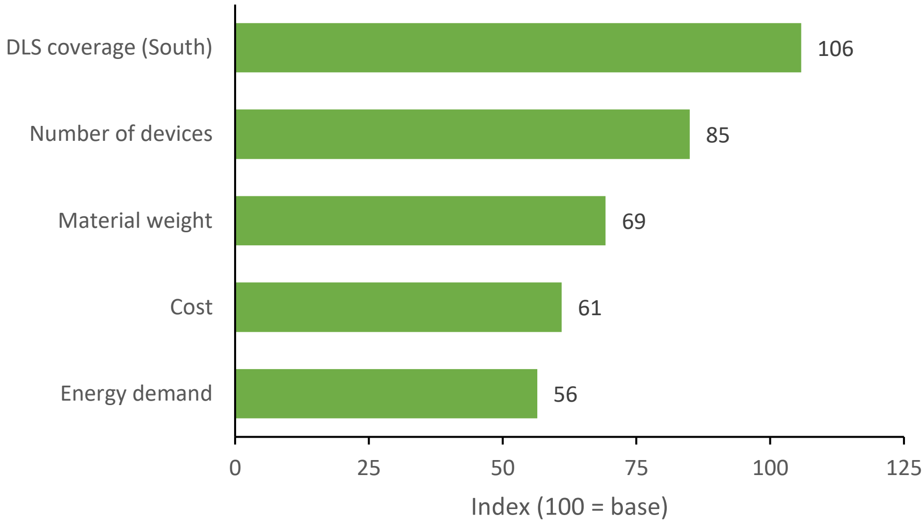
4. SOCIAL GAINS WITH ENVIRONMENTAL CO-BENEFITS

How this scenario produces social benefits including universal access to appliances and advances in climate mitigation? Digital convergence and sharing improves the access to essential services provided by appliances (e.g., lighting, food preparation, thermal comfort, communication, entertainment). On the one hand, digital convergent innovations like smartphones suppress the need for the acquisition of several devices that become redundant for providing the same services (e.g., watch media stream on phones or tablets in substitution for large TV sets). On the other hand, sharing, instead of owning, reduce the burdens for the low-income families to access larger, more expensive, devices such as washing machines, water heaters, refrigerators or freezers. We estimate that a scenario with DLS, digital convergence and sharing save 29 billion devices in 2050, corresponding to 9 trillion US dollars at the current prices. These technological and social innovations open new opportunities to democratize the access to basic goods and services by reducing the investment costs.

Lower costs mean less barriers to adoption for the poorest. Under a scenario with DLS, digital convergence and sharing, there are more 8 billion devices in the Global South than in the base case. The number of devices per capita increases in the Global South (+200% to 15) in 2050, reducing the gap to the Global North. Hence, digital convergence and sharing improve the living conditions of the more vulnerable populations in developing countries turning the widespread of decent living standards more feasible.

The new practices of production and use of consumer goods have positive effects in the environment. A lower number of devices in operation reduces in 5,547 TWh the energy demand in 2050. Moreover, the material consumption decreases 152 million tons or 31% in comparison with the base estimate for 2050. Figure 3 summarizes the social gains of a scenario with digital convergence and sharing in appliances.

Figure 3. Social gains of a scenario of digital convergence and sharing in appliances with decent living standards, in comparison with the base estimate for 2050. Index (100 = base estimate). Lower is better, except for DLS coverage where a higher number represents more social gains.



These results have strong implications for the policies. They demonstrate that a better organization of the provision of modern energy services is possible that improves the quality of life of the more deprived populations of the world. New technological and social innovations, such as digital convergence and sharing economies, can provide access to consumer goods, more rapidly, efficiently, and at the lowest cost. In these terms, the policies should focus on taping on the opportunities opened by these new trends by adopting stricter efficient standards especially in the Global South. Policies can also address more specific obstacles to the growth of sharing economies (e.g., promote the use of shared equipment in buildings) or of digital convergent innovations. In this case, several type of interventions can stimulate the uptake of these innovations (e.g., reinforcing electricity reliability as well as fast and low-cost connection contribute that smartphones and tablets replace a myriad of small and large devices).

The analysis opens new perspectives for future studies. This work offers preliminary estimates of the effects of digital convergence and sharing and thus have several limitations. Our approach builds on trends observed in several consumer goods and estimate the effects of these trends if they generalize in these categories of goods, assuming the pursuing of efficiency tendencies in both the standard and new technologies. Future research should shed more light on the technological changes expected in appliances. In particular, there is the need to identify the full range of digital convergent and sharing innovations that are available in the short-term to improve the access to essential daily services, especially in the Global South.

Further analysis should also assess possible increase in consumption of other goods and services. Even though the environmental benefits could be of several orders of magnitude by service provided largely compensating any possible rebound in consumption, increased purchasing power (from lower costs of using appliances) can grow consumption of other goods and services (e.g. travel, e-commerce) that can increase emissions (Sorrell et al., 2020). Finally, this study shows the potential of granular demand side innovations to improve the quality of life and mitigate climate change, applied to consumer goods. More research is needed to extend the methodology to other sectors (e.g., mobility, food, energy).

REFERENCES

ADEME (2019). Modélisation et évaluation environnementale de produits de consommation et biens d'équipement. Rapport RDC Environment, Décembre, 180 pages.

Bento, N. (2016). Calling for change? Innovation, diffusion, and the energy impacts of global mobile telephony. Energy Research & Social Science, 21, 84-100.

Cabeza, L. F., Palacios, A., Serrano, S., Ürge-Vorsatz, D., & Barreneche, C. (2018). Comparison of past projections of global and regional primary and final energy consumption with historical data. Renewable and Sustainable Energy Reviews, 82, 681-688.

Creutzig, F., Niamir, L., Bai, X., Callaghan, M., Cullen, J., Díaz-José, J., ... & Ürge-Vorsatz, D. (2022). Demand-side solutions to climate change mitigation consistent with high levels of well-being. Nature Climate Change, 12(1), 36-46.

ESMAP (2022). Tracking SDG 7: The Energy Progress Report: Progress Towards Sustainable Energy (Energy Sector Management Assistance Program, 2021); https://trackingsdg7.esmap.org/

Eurostat (2022). Harmonized Index of Consumer Prices. https://ec.europa.eu/eurostat/web/hicp/data/database

Gertler, P. J., Shelef, O., Wolfram, C. D., & Fuchs, A. (2016). The demand for energy-using assets among the world's rising middle classes. American Economic Review, 106(6), 1366-1401.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., ... & Valin, H. (2018). A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies. Nature Energy, 3(6), 515-527.

IEA (2020). Tracking Buildings 2020, <https://www.iea.org/reports/tracking-buildings-2020>.

IEA (2021). Appliances and Equipment, IEA, Paris https://www.iea.org/reports/appliances-and-equipment

Khosla, R., Miranda, N. D., Trotter, P. A., Mazzone, A., Renaldi, R., McElroy, C., ... & McCulloch, M. (2021). Cooling for sustainable development. *Nature Sustainability*, 4(3), 201-208.

Kikstra, J. S., Vinca, A., Lovat, F., Boza-Kiss, B., van Ruijven, B., Wilson, C., ... & Riahi, K. (2021). Climate mitigation scenarios with persistent COVID-19-related energy demand changes. Nature Energy, 6(12), 1114-1123.

Millward-Hopkins, J., Steinberger, J. K., Rao, N. D., & Oswald, Y. (2020). Providing decent living with minimum energy: A global scenario. Global Environmental Change, 65, 102168.

Oswald, Y., Owen, A., & Steinberger, J. K. (2020). Large inequality in international and intranational energy footprints between income groups and across consumption categories. *Nature Energy*, 5(3), 231-239.

Poblete-Cazenave, M., Pachauri, S., Byers, E., Mastrucci, A., & van Ruijven, B. (2021). Global scenarios of household access to modern energy services under climate mitigation policy. *Nature Energy*, *6*(8), 824-833.

Rao, N. D., & Ummel, K. (2017). White goods for white people? Drivers of electric appliance growth in emerging economies. Energy Research & Social Science, 27, 106-116.

Rao, N. D., Min, J., & Mastrucci, A. (2019). Energy requirements for decent living in India, Brazil and South Africa. Nature Energy, 4(12), 1025-1032.

Sorrell, S., Gatersleben, B., & Druckman, A. (2020). The limits of energy sufficiency: A review of the evidence for rebound effects and negative spillovers from behavioural change. Energy Research & Social Science, 64, 101439.

Wilson, C., Kerr, L., Sprei, F., Vrain, E., & Wilson, M. (2020). Potential Climate Benefits of Digital Consumer Innovations. Annual Review of Environment and Resources, 45, 113-144.

Supplementary Information

1. INTRODUCTION

The growing demand of consumer goods[4] increases the pressure on material consumption while putting at risk the efforts to limit global warming to 1.5ºC. Appliances are among the fastest growing categories of energy demand, driven by increase in revenues and rising ownership of devices (Gertler et al., 2016). They already account for 15% of global final electricity demand, or one-third of the energy consumed in buildings if lighting and cooking is included (IEA, 2017). If demand keeps increasing at the same pace, overrunning the improvements in energy efficiency, one out of six units of final energy demand in 2050 will go to consumer goods (i.e. appliances and electric plug-loads), even in a low energy demand scenario (Grubler et al., 2018). This would put at risk the efforts to reduce the energy consumption in buildings, which already account for 60% of global electricity demand, corresponding to 28% of global energy-related CO_2 emissions in 2019 (IEA, 2020).

New technological and social innovations open opportunities to conciliate the higher demands for consumer goods with the decarbonization targets. Two trends are particularly promising to reduce the energy demand from appliances, without lowering the provision of energy services (e.g. communication, entertainment, cool and heating): digital convergence and sharing economies.

Digital convergence refers to the tendency of stand-alone objects to converge onto new devices, creating hybrid "multifunctional" objects (Bainbridge & Roco, 2016). The typical example is the smartphone that converged previously unrelated technologies such as the telephone, television and computer through an increasing interplay of shared parts consisting of digital electronics and software including applications or "Apps".

Sharing economy denotes the case in which an otherwise underutilized good or service, such as cars or devices, is used by multiple people, as opposed to its ownership for individual consumption. Moving from owning to sharing presents several benefits such as more intensive

[4] Consumer goods are by definition products that consumers buy to perform one or several services (lighting, cooking, entertainment, etc.) for their own (direct) use, as opposed to capital goods that are mainly used in business. They can include all sort of plug-loads in buildings that are not fixed and dedicated to thermal comfort. Large and small household appliances, such as refrigerators and radio alarm clocks respectively, are a major group of consumer goods. For this reason, in the rest of this paper, we will be referring to these goods interchangeably as consumer goods, appliances, equipment or devices.

use of the good or service, waste minimizing (circular economy) and reduction in the material needs (dematerialization).

Sharing economy and digital convergence can therefore contribute to significantly lower the demand of consumer goods. They open promising avenues to lower both the energy demand and the material consumption from appliances. The environmental benefits could be of several orders of magnitude by service provided, largely compensating any possible rebound in consumption (Sorrell et al., 2020). More importantly, digital convergence and sharing could enable the widespread access to the services provided by modern consumer goods (entertainment, communication, lighting, etc.), particularly to the population in developing countries where their access is more limited today.

The purpose of this research is to estimate the potential of digital convergence and sharing economy to reduce the energy demand from consumer goods and to dematerialization in 2050 for meeting the 1.5ºC target and the sustainable development goals.

We develop a scenario that satisfies the demands for consumer goods in 2050 while ensuring decent living standards for all. This scenario reduces their energy demand by roughly a third and the material consumption by a fifth relatively to 2020. The results contribute to identify strategies that drastically lower the energy and material requirements from consumer goods. The analyses identify the categories of appliances with the highest potential for energy and material reductions. The regional disaggregation reveals the areas that will contribute the most for the growing demand of consumer goods, and thus should receive more attention. Finally, and more importantly, the results show that digital convergence and sharing can counteract the increase in energy demand of consumer goods from raising revenues and the provision of decent living standards, with lessons for other sectors.

The supplementary information proceeds as follows. Section 2 presents the emerging trends in consumer goods. Section 3 shows the methodology adopted in this investigation. Section 4-6 present the results of the simulations, under the different scenarios, for the number of appliances, energy demand, and material consumption. Section 7 shows the effects of alternative assumptions for the evolution of the material intensity of appliances in the material use. Section 8 concludes with a discussion of the main results and their implications for sustainability.

2. EMERGING TRENDS IN CONSUMER GOODS

We identify and review four main trends that are emerging around consumer goods, in an increasing order of disruptiveness: long-term efficiency improvement; economic and structural change; digital convergence; sharing economies.

2.1. Long-term efficiency improvement

The energy use by most appliances in buildings has considerable decreased over time. This happened thanks to the continuous improvements in the quality and performance of the products that has enhanced the equipment efficiency. Efficiency gains are around 40% for large appliances in the past three decades (Enerdata, 2020). Ratcheting minimum energy performance standards (MEPS) for appliances played an important role in this trend. MEPS cover now 80% of several large appliances like residential refrigerators in more than one hundred countries (IEA, 2021). For example, new refrigerators sold in Europe have to be 75% more efficient than a decade ago.

The efficiency gains in appliances have been counterbalanced by the rapid growth in small electric plugs whose demand is driven by revenues increase and rising ownership of devices (IEA, 2021). This has limited the decoupling between the energy consumption and the increase in the number of devices.

2.2. Economic and structural change

As for other sectors, changes in energy demand from consumer goods can be disaggregated into changes in activity, intensity and structural effects (Koomey et al., 2019). Activity is largely influenced by economic factors, such as substitution effects from changes in the relative prices of consumer goods, and income effects from lower prices or increasing available revenue of the families. Intensity of consumer goods depends on the evolution of the power unit consumption or efficiency per device. Efficiency improvement is an important trend in consumer goods, what is covered in Section 2.1. Finally, structural effects relate to changes in the weights of the categories of consumer goods, reflecting alterations in the patterns of consumption. Structural effects have been largely overlooked in the literature which has been focusing on the first two effects.

Structural effects refer to the impact produced by changes in the relative activity or numbers of the composing categories of consumer goods. In the extreme case, this could explain the paradox under which the overall energy demand from consumer goods reduces even if the consumption of a large number of categories increases.

Several factors explain the changes in the structure of consumer goods. Since structural effects depend on changes in the relative demand for each category, it is influenced by the same economic and technological effects that affect the activity for these categories in the longer run. Therefore, we can again distinguish a substitution effect and a revenue effect.

The substitution effect leads to a relative increase in the share of consumer goods for which prices reduce faster than the average. For example, the price of household appliances has been decreasing in the past decades, as shown in the 25% percent reduction in the harmonized index of consumer prices for household appliances in the European Union (Figure S1). Particularly, the price of electronic equipment has decreased faster than the rest of household appliances, as proxied by the producer price index in the United States (Figure S2). This explains the general increase in the share of electronic goods in the structure of consumer goods.

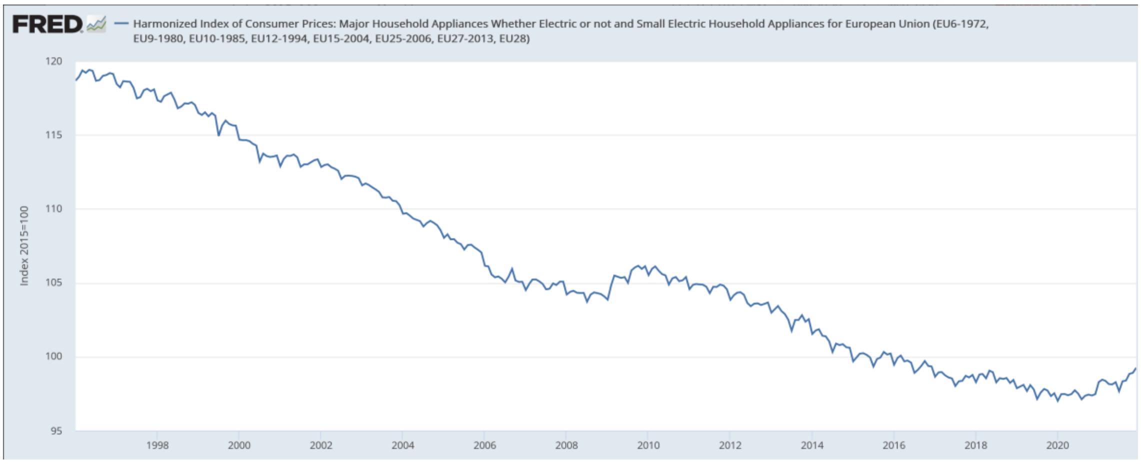


Figure S1. Harmonized Index of Consumer Prices of household appliances in the European Union, 1997-2021. Source: Eurostat: Major Household Appliances Whether Electric or not and Small Electric Household Appliances for European Union (EU6-1972, EU9-1980, EU10-1985, EU12-1994, EU15-2004, EU25-2006, EU27-2013, EU28) [CP0531EUCCM086NEST], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/CP0531EUCCM086NEST, January 21, 2022.

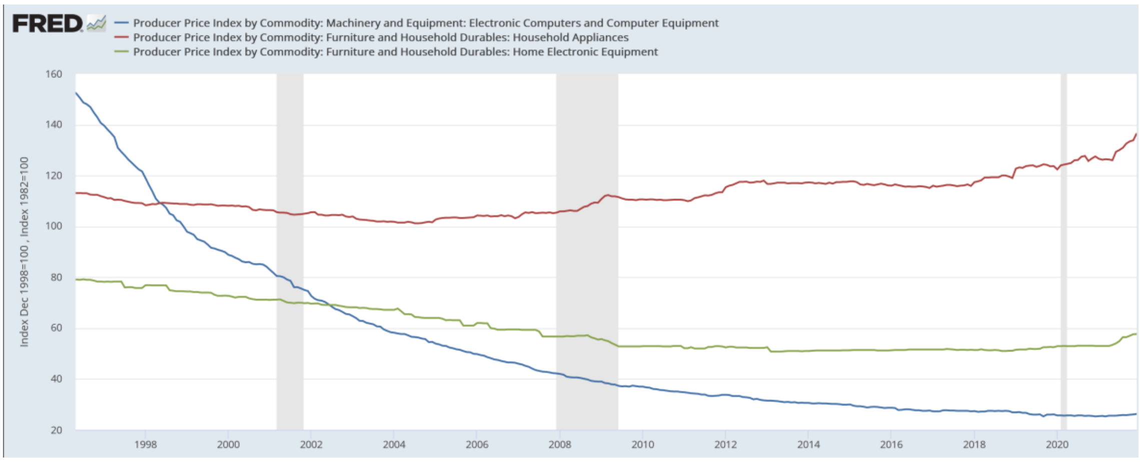


Figure S2. Producer Price Index by Commodity in the United States, 1997-2021. Source: U.S. Bureau of Labor Statistics, Producer Price Index by Commodity: Machinery and Equipment; Electronic Computers; and Computer Equipment [WPU115], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/WPU115, January 21, 2022.

The income effect results from the increase in the disposable revenue of the families following the decrease in the prices of consumer goods and/or the increase in general revenues (e.g. salaries) in real terms (after inflation). The income effect increases the consumption of all type of goods. These include more expensive, larger household appliances, which become more accessible in low-income countries in the Global South. The final effect will depend on the relative strength of these two effects. For example, if the income effect is too strong in low-income countries (with low rates of appliances ownership), one could expect an increasing share of larger appliances which have higher energy consumption.

Structural effects therefore capture substitution effects within service categories, e.g., from radio sets to mini stereo or from feature phones to smartphones. But they also include structural shifts across device categories from basic provisioning (decent living standards) to luxury items, e.g., from fans to A/C units in thermal comfort, or from hand washing with hot water (boiler) to washing machines and dryers. These structural shifts have implications in energy demand and materials use.

2.3. Digital convergence

Digitalization offers new opportunities to reduce the effects in energy, resources and emissions across the main dimensions of consumption (mobility, homes, food, energy). Digitalization impacts an increasing number of domains of social life by reorganizing them around digital technologies and media infrastructures (Brennen & Kreiss, 2016). The transition from analog to digital technologies (post mail to email, telephone call to chat) changes the way that people interact in the spheres of work or leisure (Bradley, 2017). Digital technologies are also transforming the organization of activities and business by blurring the digital and physical worlds (Gartner, 2021). Applications or “Apps”, for example, perform specific functions (tasks or services) without the need for further separated information and operational technologies.

Digital convergence is another megatrend that refers to the tendency of stand-alone objects to converge onto new devices, creating hybrid "multifunctional" objects (Bainbridge & Roco, 2016). Digital convergence can be a powerful lever for lowering energy demand and material use. This is a new topic of research that was largely put forward in Grubler et al. (2018) with the illustrative example of the substitution of physical devices by “apps” running on smartphones. Smartphones can substitute at least seventeen devices, from alarm clock to GPSs and radios, using only 2.5 watts on standby and 5 watts in use. This is thirty times less the power in standby and hundred times less the power in use that would be need by that many replaced devices (Grubler et al., 2018). Smartphones still remain ten times more efficient in service provision (in terms of energy use) when discounting the energy demand from the supporting digital infrastructure (Bento, 2016).

As for the impact on materials use, digital convergence can achieve a factor of 25 reduction in the embodied energy (including the avoided transformation of raw materials) necessary to produce the devices that have become redundant (Grubler et al., 2018). Figure S3 summarizes the contribution of smartphones for dematerialization and lower energy demand. This illustration shows the potential of digital convergence to reduce both the energy intensity of the services provision and the number of devices in use (dematerialization).

Figure S3. Digital convergence and dematerialization: illustrative example with the smartphone. Sources: Grubler et al., 2018; Bento, 2016.

Electronic consumer goods need relatively more energy in production than other consumer goods (ADEME, 2019). Smartphones are very efficient in operation with direct energy consumption corresponding to only 3% of the overall energy impact. But 97% of the impact of smartphones comes from the embodied energy, i.e. the energy necessary to produce the materials which enter into their production. These numbers compare with 63% (direct energy) and 37% (embodied energy) in the case of a typical refrigerator (Figure S4). However, the total energy demand can still be significantly lower in small electronic goods such as smartphones than in refrigerators, even if adjusted for the shorter lifetime of the formers (3 years instead of 15 years for fridges).

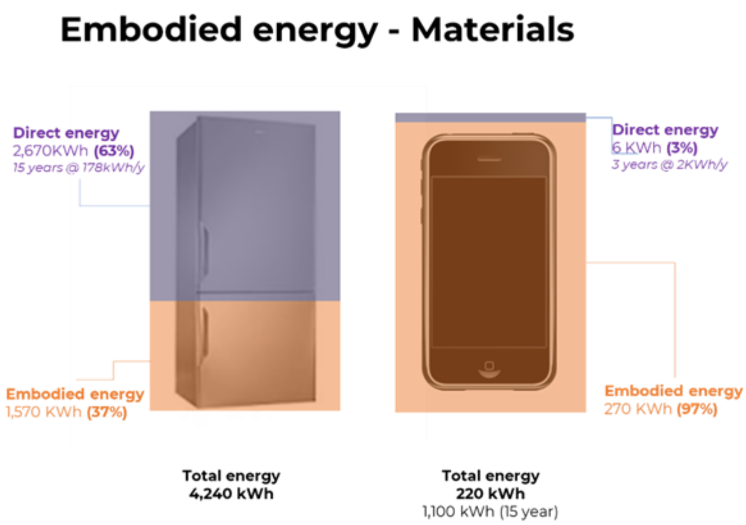


Figure S4: Comparing direct and indirect (embodied) energy of a refrigerator versus mobile phone. Source: compiled by the author from several sources.

The literature is scarce on the effects of digitalization on energy demand. IEA (2017) concludes that the digitalization impacts can significantly change within scenarios and across energy demand sectors (transport, buildings and industry). Another rare study, Wilson et al. (2020) surveys the literature about a number of digital innovations across several domains (mobility, food, homes and energy). The authors show evidence of a clear potential of digital consumer innovation for emission reductions. However, they also point to some studies that indicate possible demand increases due to rebound effects and substitution effects.

2.4. Sharing economy

Sharing economy is a complex phenomenon which in the last decade has been able to influence not only worldwide customers behavior but also incumbents' business models and their profitability (Gislon, 2020). The sharing economy is a peer-to-peer activity that allows people to share or obtain goods and services, often through online platforms.

Sharing is the main principle. It refers to the case in which a good or service, such as cars, houses or devices, is used by multiple people, as opposed to its ownership for individual consumption. Moving from owning to sharing presents several benefits such as more intensive use of the good or service, minimizing material needs (dematerialization) and waste (circular economy).

Single-owned devices are often underutilized. For example, a privately owned car is typically parked the largest part of its lifetime. This fact together with the increase in congestion in the cities has increased the interest for shared mobility services over personally owned transport modes. Mobility-as-as-Service or simply MaaS is an emerging concept which concentrates multiple mobility services (of different types and providers, both public and private) in a single platform (most often, a journey planner) where users can create and manage their trips. MaaS encompasses a wide range of emerging mobility services, from sharing the rides (e.g. carpool) to the means (bicycle-, scooter-, car-sharing) or even shared (mini)buses. As for the later, in a study for the city of Lisbon, ITF (2015) has estimated that the deployment of shared mobility (cars and mini-buses) could reduce a large number of cars (to 3% of the today's fleet) and congestion. It has been estimated that almost 2 million cars were not sold in 2016 in the world due to ride-sharing apps, with particular impact in China (960 thousands) and India (540 thousands) (Statista, 2022). The number of users of shared mobility has been increasing even during the pandemics and reached 44.2 million in car sharing, 49.3 million in e-scooter sharing, and 669.3 in bike sharing in 2020 (Statista, 2021).

Sharing allows more intensive use of houses as well. As of 2019, Airbnb has served 500 million people with over 6 million Airbnb listings in more than 191 countries and regions. Peer-to-peer accommodation platforms such as Airbnb have become an important part of the tourism and hospitality industry, replacing to some extent the need for the construction of additional hospitality capacity (Zhang et al., 2020).

Sharing improves efficiency and reduces the costs of the use. Sharing, rather than owning, appliances and services allow that devices can be used more intensively, at a higher load factor, more often. Thus, shared devices can run more efficiently at the lowest energy consumption and operational cost (Ivanova et al., 2020). Several devices are increasingly shared at the buildings or community levels. For example, washing machine rooms are not unusual in multifamily buildings in North America and increasingly in Europe and other parts of the world like. Likewise, laundry shops become common in many cities of the world. Another example is the increasing centralization of equipment such as Heating, Ventilating and Air Conditioning (HVAC) systems at the building level. Sharing has the potential to reduce the number of devices by centralizing equipment (e.g. washing machines, water heaters and ventilation).5

[5] We were unable to find estimates for the carbon reductions obtained by sharing equipment (HVAC, washing rooms, etc.), instead of single-owned by the household, at the building level. The benefits of sharing equipment in multi-family or multipurpose buildings enter in the studies that compare the energy and carbon footprint in urban

Sharing instead of owning reduces material requirements. Sharing reduces the number of devices that are required to serve the same service (lighting, entertainment, hygiene, etc.). By lowering the number of devices through their collective use, sharing has the potential to reduce the embodied energy associated to the avoidable goods (Ivanova et al., 2020). In so doing, sharing contributes to reduce the number of devices that have to be produced and disposed at the end, relieving the pressure on waste management and recycling. Overall, sharing lowers the direct and indirect emissions of the devices.

Co-living, co-working and shared building infrastructure are other types of flexible usage that are representative of sharing. Co-living is the most common way of sharing. A five or more average household in EU has half of carbon and energy footprint that of a one-person average household (Ivanova & Büchs, 2020). Collective living or working improves the possibility that people share more amenities such as lighting, space heating/cooling, living spaces, appliances and other equipment (Ivanova et al., 2020; Fremstad et al, 2018; Wiedenhofer et al., 2018). Collective living (including renting out guest rooms) reduce in average 0.3 tCO2eq/cap per year (Ivanova et al., 2020).

The few number of studies we found that estimate the benefits of sharing (e.g. Ivanova & Büchs, 2020; Fremstad et al., 2018) use statistical and econometric analysis of household surveys (e.g. Household Building Surveys from Eurostat, US Consumer Expenditure Survey), crossed with estimates of the products' energy and carbon footprint calculated, for example, from input-output databases (e.g. EXIOBASE).

The studies tend to analyze the potential of sharing in terms household economies of scale, as well as on the relation between household size and density (see a review in Ivanova & Büchs, 2020). Adding one person more to a one-member household can significantly reduce the energy consumption and material footprint, however the marginal gains of further increases become much smaller. After some threshold, the economies of scale may exhaust, and thus increases in the size of the household implies reinforcement in lighting, HVAC, appliances, water supply, among others. On the other hand, more densely populated and compact urban areas tend to be regarded as presenting higher opportunities for resources sharing between households (Gill & Moeller, 2018). But urban areas also attract more wealthy population (Poom & Ahas, 2016), living in smaller size households (Ivanova & Büchs, 2020), that counterbalance the effects of density. Thus urban areas can present household economies of

---

areas and rural areas through the general concept of household economies of scale. Still there is no explicit estimation of the potential of sharing equipment for reducing the energy demand of buildings.

scale that are lower than in suburban areas (Ottelin et al., 2015). Several empirical studies show lower potential for further household economies of scale in urban contexts compared to rural areas, though with lower emissions per capita in the cities (e.g. Fremstad et al., 2018).

There is still a lack of systematic analysis of the way that new megatrends such as digitalization, dematerialization and sharing impact on the energy efficiency of the appliances and have the potential to shift demands across types of appliances with an effect in the overall energy demand.

3. ESTIMATING THE IMPACTS ON ENERGY DEMAND AND MATERIAL CONSUMPTION

The section starts by presenting the methods followed to estimate the demand for consumer goods, as well as the resulting energy and material implications, both in 2020 and in 2050 in the base (or reference) case (Section 3.1). Then we explain the calculations of the effects of generalizing decent living standards (Section 3.2), digital convergence (Section 3.3) and sharing the devices (Section 3.4).

3.1 Base case

We depart from the projections for the demand of consumer goods in the base year of 2020. These projections come from the GEA Efficiency scenario (Ürge-Vorsatz et al., 2012), which was recently re-estimated in the Low Energy Demand (LED) study (Grubler et al., 2018). Similarly to LED, we estimate the demand for appliances from both the residential sector and the commercial/services sector.

We estimate the demand by major types of consumer goods. Comparing to LED or GEA Efficiency, we consider a finer-grained categorization of the consumer goods into: hygiene (e.g. hot water, washing machine); food preparation (e.g. refrigerator, electric stove); communication & entertainment (e.g. mobile phone, television, personal computer); lighting (all types of lamps), thermal demand (e.g. fan, portable air conditioner), and miscellaneous (mainly consisting on small electric load devices, e.g. set-top boxes, routers, smart speakers). See Table S1.

Table S3. Consumer goods and key sources[6]

Appliance	*Category*	*Number of devices*	*Energy consumption*	*Service*
Lamps	Lighting	NAS, VITO	VITO, WB, Gifford et al.	VITO
Washing machines	Hygiene	Pachauri	McNeil et al., Ruedenauer et al.	EC, Ruedenauer et al.
Water heater	Hygiene	Pachauri, GMI	IEAa	IEAa
Refrigerator	Food preparation	Pachauri, EUI	McNeil et al., GEA	IEAb
Freezer	Food preparation	Pachauri, IEAb	IEAb	IEAb
Electric stove	Food preparation	Industry Research	WB	(various)
Electric oven	Food preparation	Amienyo et al.	WB	(various)
Television	Communication & entertainment	ITU, Pachauri	McNeil et al, GEA, WB	WB
Mobile phone	Communication & entertainment	ITU, Pachauri	Bento	GSM Arena, Bento
PC	Communication & entertainment	ITU, Pachauri	WB	WB
Fan	Thermal demand	Pachauri	WB, BRE, Cabeza et al, Radgen et al	BRE
Portable air conditioner	Thermal demand	Hitchin et al.	WB	BRE
Small electric load devices	Miscellaneous	EWEB	EWEB	-
Productive power and thermal	Productive uses	IEAc	IEAc	-

6 NAS-National Academies of Sciences, Engineering, and Medicine. 2017. Assessment of Solid-State Lighting, Phase 2. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/24619.

VITO, Preparatory Study on Light Sources for Ecodesign and/or Energy Labelling Requirements: Final Report, Task 7, published online 31 October 31, 2015.

World Bank, 2008. Residential Consumption of Electricity in India, Documentation of Data and Methodology, World Bank draft report, July 2008. Electronic version.

Gifford, W. R., Goldberg, M. L., Tanimoto, P. M., Celnicker, D. R., & Poplawski, M. E. (2012). Residential lighting end-use consumption study: Estimation framework and initial estimates (No. PNNL-22182). Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

Pachauri S., Poblete Cazenave M. (2020), Personal Communication, IIASA (ENE-TNT).

EUI (2019). The cooling imperative: Forecasting the size and source of future cooling demand. The Economist Intelligence Unit. The Economist.

GMI - Global Market Insights https://www.grandviewresearch.com/industry-analysis/water-heaters-market (23/1072020)

Amienyo, D., Doyle, J., Gerola, D., Santacatterina, G., & Azapagic, A. (2016). Sustainable manufacturing of consumer appliances: Reducing life cycle environmental impacts and costs of domestic ovens. Sustainable Production and Consumption, 6, 67-76.

A. McNeil et al, Global Potential of Energy Efficiency Standards and Labeling Programs, CLASP, November 2008.

GEA- Ürge-Vorsatz, D., N. Eyre, P. Graham, D. Harvey, E. Hertwich, Y. Jiang, C. Kornevall, M. Majumdar, J. E. McMahon, S. Mirasgedis, S. Murakami and A. Novikova (2012). Chapter 10 - Energy End-Use: Building. In Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 649-760.

IEAa (2012). Water Heating . Energy Technology Systems Analysis Programme (ETSAP), IEA, Technology Brief R03, June 2012, www.etsap.org

IEAb (2012). Cold Appliances. Energy Technology Systems Analysis Programme (ETSAP), IEA, January, www.etsap.org

Ruedenauer, I., Blepp, M., Brommer, E., Gensch, C., Graulich, K., Mudgal, S., ... & Seifried, D. (2011). Preparatory studies for Ecodesign Requirements of energy-using products: Lot 24: professional washing machines, dryers and dishwashers; Final Report, Part Dishwashers.

EC - European Commission (2019). Accompanying the document on laying down ecodesign requirements for household washing machines and household washer-dryers and with regard to energy labelling of household washing machines and household washer-dryers, Commission Staff Working Document, Impact Assessment, Brussels, 1.10.2019, SWD(2019) 349 final PART 2/2.

ITU World Telecommunication/ICT Indicators Database (2020). https://www.itu.int/en/ITU-D/Statistics/Documents/statistics/2020/CoreHouseholdIndicators%20%2820-08-20%29.xlsx (last access in August 2020)

Bento, N. (2016). Calling for change? Innovation, diffusion, and the energy impacts of global mobile telephony. Energy Research & Social Science, 21, 84-100

GSM Arena (2020), Battery life test results, https://www.gsmarena.com/battery-test.php3?idPhone=9846#show (last access 14/10/2020).

Hitchin, R., Pout, C., & Riviere, P. (2013). Assessing the market for air conditioning systems in European buildings. Energy and Buildings, 58, 355-362.

BRE, U. (2009). Preparatory study on the environmental performance of residential room conditioning appliances (airco and ventilation). Policy.

Cabeza, L. F., Ürge-Vorsatz, D., Ürge, D., Palacios, A., & Barreneche, C. (2018). Household appliances penetration and ownership trends in residential buildings. Renewable and Sustainable Energy Reviews, 98, 1-8.

Radgen, P., Oberschmidt, J., & Cory, W. T. (2008). EuP Lot 11: Fans for ventilation in non residential buildings Final Report. European Commission, 1-202.

EWEB (2019). Typical Residential Electricity Use and Cost. Eugene Water & Electric Board, www.eweb.org

IEAc (2020). IEA World Energy Balances 2020 https://www.iea.org/subscribe-to-data-services/world-energy-balances-and-statistics

To validate the estimates for the global stock of appliances in 2020, we compare with the actual numbers for the global stocks of major appliances (e.g. refrigerators, televisions, washing machines). Numbers of the stock of appliances in use are available from several sources, including the national statistics of the main regions such as the US7 and Europe.8 To highlight the different dynamics in the rising ownership of devices, namely from the wealthiest developing countries, we expand the spatial resolution to 11 regions from the 2 regions (global North and global South) in LED (Appendix 1).

The level of stocks of consumer goods (activity) here estimated serves as the basis for the estimation of the impact on the energy demand and on the materials consumption (the latter is explained below).

We use typical disaggregation analysis (à la Kaya) to derive the energy demand from consumer goods, by major group of appliances, and by region. More specifically, we consider the following disaggregation method:

$$\text{Energy demand (TWh)}_{ij} \;=\; \sum_{ij} h_j . \frac{n_j}{h_j} . \frac{u_i . W_i}{n_i}$$

for the consumer good *i* and the country *j*. We can recognize here two components:

- **activity**: changes in the number of consumer goods (*n*) or in the number of devices per household ($h . \frac{n}{h}$). Alterations in activity have two main sources: 'Demographic' for changes in the number of households (*h*) through alterations in the population (*p*) or in the average number of people per household (*h'* where *h=population/h'*); and 'Ownership' for changes in the average number of devices per household (*n/h*);

- **intensity**: changes in the energy consumption per appliance. Intensity can further be decomposed into two main terms: 'Usage' (or load factor) for changes in the annual number of hours of use per device (*u*); and 'Efficiency' for changes in the average power (or wattage) of the appliances (*W*).

7 e.g.: U.S. Energy Information Administration (2020), Office of Energy Consumption and Efficiency Statistics: https://www.eia.gov/consumption/residential/data/2015/hc/php/hc3.1.php (last access August 4, 2020).

8 For example, from the European Commission's EU Buildings Database: https://ec.europa.eu/energy/eu-buildings-database_en (last access August 4, 2020).

The base projections take into account the trends observed in efficiency over time. We revise the estimates for the energy efficiency of appliances in 2020 that were made in LED, which in turn updates the estimates in GEA (Ürge-Vorsatz et al., 2012), with the most recent data. Data is available for several types of appliances in Europe9 and Japan (METI, 2015). In addition, we assume the same improvements in energy efficiency of appliances between 2020 and 2050 as in LED.

As for the stock of consumer goods in 2050, we estimate the demand of devices based on the revenue per capita in that year. The base projections consider the historical relationship between the number of devices per 100 persons and the level of GDP per capita. Figure 1 shows the high correlation between applications ownership (i.e. number of devices per 100 persons) and the GDP per capita of the different regions in the world.

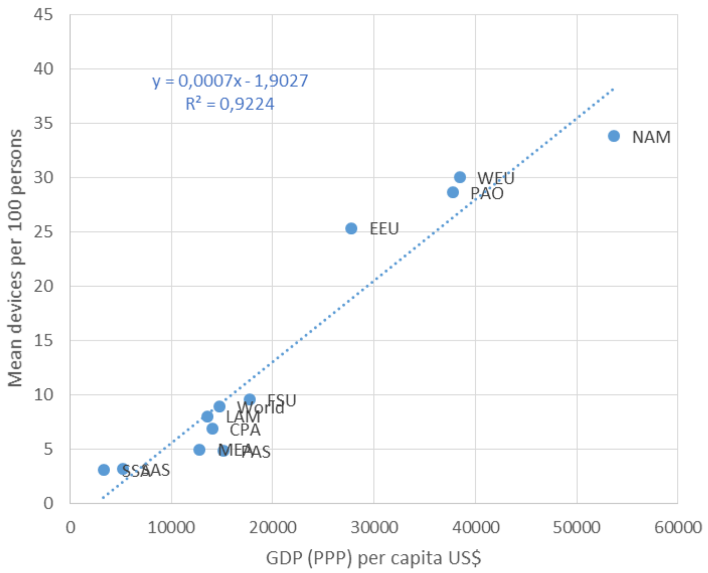


Figure S5. Correlation between the average number of appliances per 100 persons (including in the commercial sector) and GDP per capita, world and by region.

We start by computing the GDP per capita (at parity purchasing power, PPP), by main regions, using the projections for GDP and population in 2020 and 2050 that are available in the IPCC's Shared Socioeconomic Pathways (SSPs) database.[10] Then, we correlate the number of devices in use per 100 persons, per category, in 2020, with the GDP per capita by region. We take the

[9] e.g.: https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/trends-europe.html (last access August 4, 2020)

[10] SSP database hosted by the IIASA Energy Program at https://tntcat.iiasa.ac.at/SspDb (download in 15/10/2020).

best fits to estimate the number of appliances in use by category in 2050, taking into consideration the projections for the GDP per capita in that year from the SSPs database. We assume that the trend between revenue and device ownership remains stable over time. Appendix 2 lists the type of equation and the parameters assumed for the calculation of the number of devices (activity) by category in 2050.

This is an enormous improvement in the projections of the number of devices over previous studies. LED, for example, computes demand by using average ownership rates in only two regions (Global North and Global South). The present revision not only explicitly considers a larger range of devices as it computes the demand for appliances for the 11 regions, separately. It further takes into account the differences in revenue per capita, what is conceptually more correct.

We estimate the energy demand from consumer goods in 2050 based on the projections for the number of units and the assumption for the energy intensity, following the decomposition method presented above.

In parallel to the estimation of activity and energy demand, we also calculate the services provided by consumer goods as well as the ecological footprint. More specifically, we provide estimates for the level of energy services provided (billion lumens, thousand tons of washed laundry, etc.), material intensity (by weight and by volume), and annual material flows. The level of energy services is calculated by device using information about its average (annual) use (load factor) and the service performed by a typical model.

Material impacts are an important consequence of the increase in the demand for consumer goods. We analyze these impacts in terms of both stocks of materials and annual flows.

Material stocks refer to the inputs that are necessary to produce the number of appliances in use at each moment. We estimate the material requirements based on the high correlation observed between the wattage of the devices that are representative of each type of appliance and their weight (Figure 2, right-hand). We use this correlation to estimate the average weight per type of device. Then we multiply this (material intensity) by the stock of devices to obtain the total material requirements in terms of weight. On the other hand, the volume footprint results from the calculation of the typical volume of the devices by using the correlation with their average weight (Figure 2, left-hand), multiplied by the number of devices.

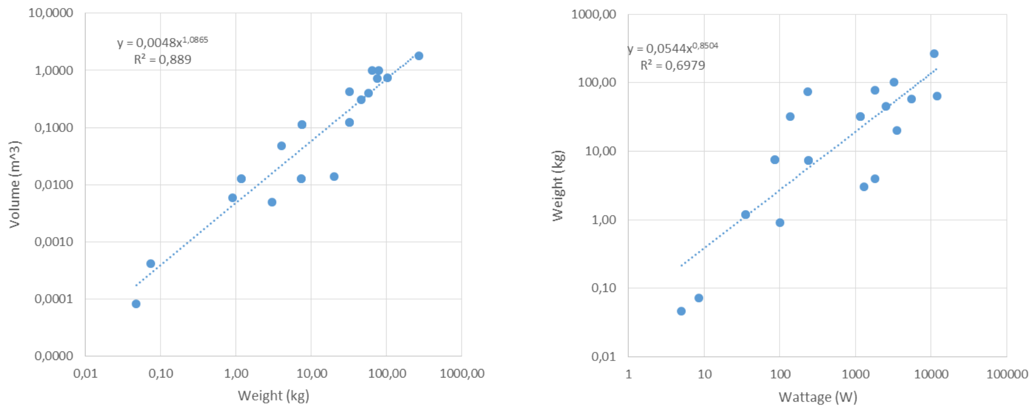


Figure S6. Correlation between weight (in kg) and Wattage (W) (right-hand graph), and between volume (m3) and weight (kg) (left-hand graph). Log-log scales.

Annual material requirements refer to the quantity of inputs that are necessary to produce the new devices that are going to replace the old ones arriving to the end of their lifetime. We estimate the annual flows by dividing the stock of devices by their lifetime, per type of appliance. Table S2 lists the assumptions considered for the lifetime of the appliances.

Table S4. Assumptions for the lifetime of consumer goods in 2020 and 2050, in years[11]

Sector	Category	Appliance	2020	2050	Source
Residentia	Lighting	Lamps	3	6	OSRAM, Richet et al., 2019
	Hygiene	Washing machine	13	15	Reale et al., 2019
		Water heater	17	17	Kemna et al., 2007
	Food preparation	Refrigerator	15	15	Reale et al., 2019
		Freezer	15	15	Reale et al., 2019
		(electric) Stove	13	13	HWA, 2020
		(electric) oven	13	13	HWA, 2020
	Communication & entertainment	Television	6	6	Reale et al., 2019
		Mobile phone	3	3	Bento, 2016
		PC (internet access)	5	5	Reale et al., 2019 (laptop)
	Thermal demand	Fan	10	10	BRE, 2009
		Portable air conditioner	15	15	Reale et al., 2019
	Miscellaneous	Small electric load devices: set-top	3	3	own assumption (electronics)
Commercia	Lighting	Lamps	3	6	OSRAM, Richet et al., 2019
	Hygiene	Washing machine	6	6	Bio Intelligence Service, 2011
		Water heater	13	13	IEA ETSAP, 2012
	Food preparation	Commercial refrigeration	10	10	JRC, 2014
		Industrial refrigeration	12	12	Climatetech, 2020
		(electric) Stove	15	15	Climatetech, 2020
	Communication & entertainment	Television	6	6	Reale et al., 2019
		PC (internet access)	5	5	Statistica, 2020
	Thermal demand	Fan	10	10	BRE, 2009
		Portable air conditioner	15	15	Reale et al., 2019
	Productive uses	Power in agriculture, fishery, etc.	13	15	own assumption (same as washing machines)
		Heating in agriculture, fishery, etc.	15	15	own assumption (same as portable ACs)

[11] OSRAM (2020), https://www.osram-group.com/en/sustainability/environmental/product-lifecycle-management/lca-incandescent

Appendix 4 lists the main inputs used in the material analysis. The shares of the main materials (steel, aluminum and plastics) come from the analysis of the bill of materials (BOM) of typical products that are provided by the manufacturers. The only exception is light bulbs for which we consider an "artificial" BOM that combines the material distribution of each one of the three main technologies in the market (conventional, CFL and Led). In addition, we calculate the embodied energy of the appliances, which includes the energy required for raw materials extraction and for manufacturing, while excluding transportation. For that we based on the estimates that are published in the literature (see sources in Appendix 4).

Therefore, the estimations for the number of devices, energy demand and materials consumption revise those in LED and serve as reference case or base (LEDbase) against which more aggressive scenarios will be compared.

To study the potential for reducing the energy demand and materials consumption from consumer goods, we formulate additional assumptions concerning the evolution of both demand and devices. This evolution should be influenced by three main trends: the widespread access to consumer goods and more generally to decent living standards for all particularly in the Global South; digital convergence with the emergence of multipurpose devices such as the smartphone performing several tasks; and the sharing economy with the

---

Richter, J. L., Tähkämö, L., & Dalhammar, C. (2019). Trade-offs with longer lifetimes? The case of LED lamps considering product development and energy contexts. Journal of Cleaner Production, 226, 195-209.

Reale, F, Castellani, V, Hischier, R, Corrado, S, Sala, S,Consumer Footprint -Basket of Products indicator on Household appliances, EUR 29758 EN.

Kemna, R., Van Elburg, M., Li, W., & van Holsteijn, R. (2007). Eco-design of water heaters. Draft reports of tasks, 1-5.

HWA - Home Warranty of America (2020), https://www.hwahomewarranty.com/learning-center/homeowners/how-long-will-appliances-last

Bento, N. (2016). Calling for change? Innovation, diffusion, and the energy impacts of global mobile telephony. Energy Research & Social Science, 21, 84-100.

BRE, U. (2009). Preparatory study on the environmental performance of residential room conditioning appliances (airco and ventilation). Policy.

Bio Intelligence Service (2011), Preparatory studies for Ecodesign Requirements of energy-using products: Lot 24: professional washing machines, dryers and dishwashers; Final Report, Part Dishwashers.

IEA ETSAP (2012). Cold Appliances. Energy Technology Systems Analysis Programme (ETSAP), IEA, January, www.etsap.org

JRC (2014). Ecodesign for commercial refrigeration. Final Report. JRC Technical Reports. European Commission.

ClimateTech (2020), https://theclimatetech.com/commercial-kitchen-equipment-average-lifespan/

Statistica (2020), https://www.statista.com/statistics/267465/average-desktop-pc-lifespan/

growth of new models of consumption based on the use, rather than ownership, of the device. These three trends have contrasting effects: decent living standards contribute to increase the demand for consumer goods, while digital convergence and sharing economies work to reduce the number of devices. We study the effects of these three trends through simulation analysis using an Excel spreadsheet. Next, we explain more in detail the estimation of the effect of each one of the three trends.

3.2. Decent living standards

At the level of decent living standards (DLS), we test the effect of different assumptions for the number and the diversity of appliances per person (or per household) that ensures basic material living conditions (Rao et al., 2019). DLS comprise a diverse set of essential items such as mobile phone, television, refrigerator, stove and electric lamp. A recent literature agrees around a minimum endowment of consumer goods that is necessary for an individual or a household to achieve DLS (e.g., Millward-Hopkins et al., 2020). Table S3 shows the assumptions considered in this study following this literature.

Table S5. Decent living standards

				2020	2050	
Category	**Appliance**	**Service**	**Unit**	**ownership per 100 HH**		**Source**
Lighting	Lamps	2500	lumens/house	400	400	Millward-Hopkins et al., 2020
Hygiene	Washing machine	80	kg washing/year	100	100	Millward-Hopkins et al., 2020
	Water heater	20	liters/cap/day	100	100	Millward-Hopkins et al., 2020
Food preparation	Refrigerator	1	fridge-freezer	100	100	Millward-Hopkins et al., 2020
	Freezer					our assumption
	(electric) Stove			*	100	our assumption
	(electric) oven			*	100	our assumption
Communication & entertainment	Television	1	TV	100	100	Rao & Ummel, 2007; Rao & Min, 2018
	Mobile phone	1	phone person over 10 years old	300	300	Millward-Hopkins et al., 2020
	PC (internet access)	1	laptop	100	100	Millward-Hopkins et al., 2020
Thermal demand	Fan	15	m2/cap (cooling)	400	100	Millward-Hopkins et al., 2020
	Portable air conditic	15	m2/cap (cooling)		100	Millward-Hopkins et al., 2020
Miscellaneous	Miscellaneous					

* can work on gas in 2020.

Our approach consists of comparing the ownership of consumer goods in the base case with these minimum thresholds by region, particularly in the Global South. If the ownership is lower than the minimum threshold, we estimate the number of devices and the respective additional energy demand that would be necessary to ensure the access to decent living standards for all.

3.3. Digital convergence

Digital convergence can reduce both the number of devices and the energy intensity of the provision of the services (e.g., watching media in a mobile phone instead of a television). This is a new topic of research and the literature is extremely limited. We will use some recent works on the potential of digitalization of consumer innovations (e.g., Wilson et al., 2020).

We analyze the effects of digital convergence focusing on the electronic devices. This concerns mainly communication and entertainment goods and miscellaneous small plug-in loads. For the formers, we study the effect of the convergence of PCs/laptops, televisions and mobile phones into a single media device. This “super” device could provide portable communication and entertainment, as well as be used for productive uses (alone or connected to other devices). In the commercial sector, this corresponds to the widespread of single multimedia device such as all-in-one interactive TV systems already available in the medium to high-end range hotels. Finally, for small plug-in loads, we assume a reduction in the number of devices that would become redundant by the converging devices. We already observe a reduction in the number of some plug-loads which are substituted by services provided by applications (“apps”) in smartphones (alarm clocks, radio set, VCR, etc.).

3.4. Sharing economies

We examine the potential for reducing energy and materials consumption by lowering the number of devices through their collective use. Sharing equipment lowers the energy and carbon footprint of households (Ivanova & Büchs, 2020; Ivanova et al., 2020). Sharing reduces the number of devices necessary to serve the same needs for lighting, entertainment, hygiene, etc. In addition, the devices can be used more intensively (higher load factor), more efficiently (at the lowest energy consumption and cost) or both.

We consider that one third of the population below 30 and above 65 years old co-live in shared houses, hosting in average 10 households, in 2050. This would assume the pursuit of the trend for co-living in these categories of age for several reasons (schooling, early-career needs, retirement, socializing, etc.) (CBRE, 2020).[12] Co-living reduce the number of appliances needed for lighting or food preparation such as lights, refrigerators, freezers, stoves and ovens (Ivanova & Büchs, 2020).

[12] Guardian (2019), 'Co-living': the end of urban loneliness-or cynical corporate dormitories?', 3/9/2019.

On the other hand, several devices are increasingly centralized at the level of buildings or at the level of the community. For example, washing machine rooms are not unusual in multifamily buildings in North America and are increasingly see in other parts of the world like in Europe, whereas laundry shops open almost everywhere. Another example is the increasing centralization of equipment such as Heating, Ventilating and Air Conditioning (HVAC) systems at the building level. Therefore we examine the possibility to reduce the number of appliances and equipment by centralizing washing machines, water heaters and portable air conditioners.

Table S4 summarizes the assumptions for digital convergence and sharing economies.

For the rest of the paper, we develop the following scenarios:

- LEDbase: 11-regional interpretation of the original LED (cf. Grubler et al., 2018, which updated the scenario GEA Efficiency for 2020, cf. Ürge-Vorsatz et al., 2012), energy use remains largely the same, number of devices changes due to the new categorization;
- LEDrev: revision of LEDbase explicitly considering impacts of assuring DSL for all (+), digital convergence (-), and sharing economy (-);
- LEDrev-LW: scenario sensitivity on LEDrev considering lightweighting of products (decrease in material intensity to a third of the levels in 2020);
- LEDrev-LW-LTX: scenario sensitivity on LEDrev-LW considering a 25% extension in the lifetime of every appliance.

Table S6. Assumptions for the calculation of the potential of digital convergence and sharing economies

Sector	Category	Appliance	Type	Sharing HH	Share level	Devices per 100 HH	Energy intensity	Observations
Residential	Lighting	Lamps	sharing	10	age		double	1/3 of the population <30 years and >65 years share houses with in average 10 HH
	Hygiene	Washing machine	sharing	10-100	building, age, urban.		double	1/2 of the urban population served by laundry shops (1 100HH); multifamily (urban) buildings and co-living (elderly, young, etc.) share laundry room (10HH)
		Water heater	sharing	10	age, building		double	shared in co-living houses in avg by 10HH (young, elederly); shared at the building level
	Food prepa	Refrigerator	sharing	10	age		double	1/3 of the population <30 years and >65 years share houses with in average 10 HH
		Freezer	sharing	10	age		double	1/3 of the population <30 years and >65 years share houses with in average 10 HH
		(electric) Stove	sharing	10	age		double	1/3 of the population <30 years and >65 years share houses with in average 10 HH
		(electric) oven	sharing	10	age		double	1/3 of the population <30 years and >65 years share houses with in average 10 HH
	Communic	Television	digital convergence			0	unchanged	converge into "all-in-one" mobile device
		Mobile phone	digital convergence			100	unchanged	1 per capita; no impact on energy intensity (kWh/year) as compensated by cut in standby
		PC (internet access)	digital convergence			0	unchanged	converge into "all-in-one" mobile device
	Thermal de	Portable air conditioner	sharing	10	building		double	shared at building level
	Miscellane	Misc. electric loads	digital convergence			33	unchanged	divide by 3 the number of electric loads as an effect of digital convergence
Commercia	Hygiene	Water heater	sharing	10	building		unchanged	shared at building level (including malls and residential buidlings)
	Communic	Television	digital convergence			0	unchanged	high load factor compensated by improved efficiency and cut in standby
		PC (internet access)	digital convergence			100	unchanged	converge to super TVs than can serve as workstations whenever needed
	Thermal de	Portable air conditioner	sharing	10	building		unchanged	shared at building level (including malls and residential buidlings)

4. IMPACT ON THE NUMBER OF DEVICES

We estimate the growth in the demand for consumer goods from 2020 to 2050 by comparing the growth in the base scenario (LEDbase) with the increase in the number of devices assuming the adoption of decent living standards, digital convergence and sharing economies (LEDrev). Figure S7 shows the results for the decomposition analysis at the global level.

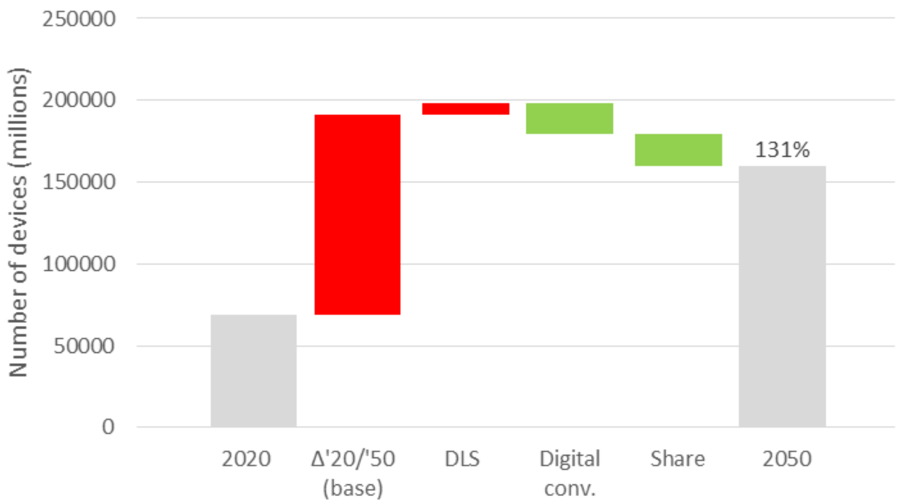


Figure S7. Disaggregation of the growth in the number of appliances in 2050 in terms of the effect of growth in the base scenario (LEDbase), decent living standards (DLS), digital convergence and sharing economies (2050=LEDrev).

The number of devices in 2020 has been revised downwards due to a more detailed analysis of a larger number of appliances, using the most recent data. We estimate the global stock of consumer goods at around 69 billion units, instead of the 105 billion assumed in LED for the base year.

In 2020, the 69 billion units provided a wide range of services that are calculated in Appendix 3. In the residential sector, for example, mobile phones supported thousands of billions of hours of talk, web browsing or video watching. Similarly, washing machines handled almost a million tons of laundry washed, while refrigerators and freezers refrigerated half of a billion cooling liters.

In the base scenario (LEDbase), the number of consumer goods increases 177% to reach 191 billion units in 2050. This growth is mainly explained by the increase in demand from the Global South (+107 billion units) that is driven by the growth in the revenue per capita (Table S5). The expected rise in revenue also explains the relative modest additional growth of devices (+7 billion) that would be needed to ensure decent living standards for all. Digital convergence more than compensates that growth, contributing to decrease the number of devices in 19 billion. Finally, sharing devices would further cut the need of 20 billion devices. Taken together, in the LEDrev scenario, digital convergence and sharing would limit the increase in the number of devices to 160 billion units (+131% or less 46 percentage points).

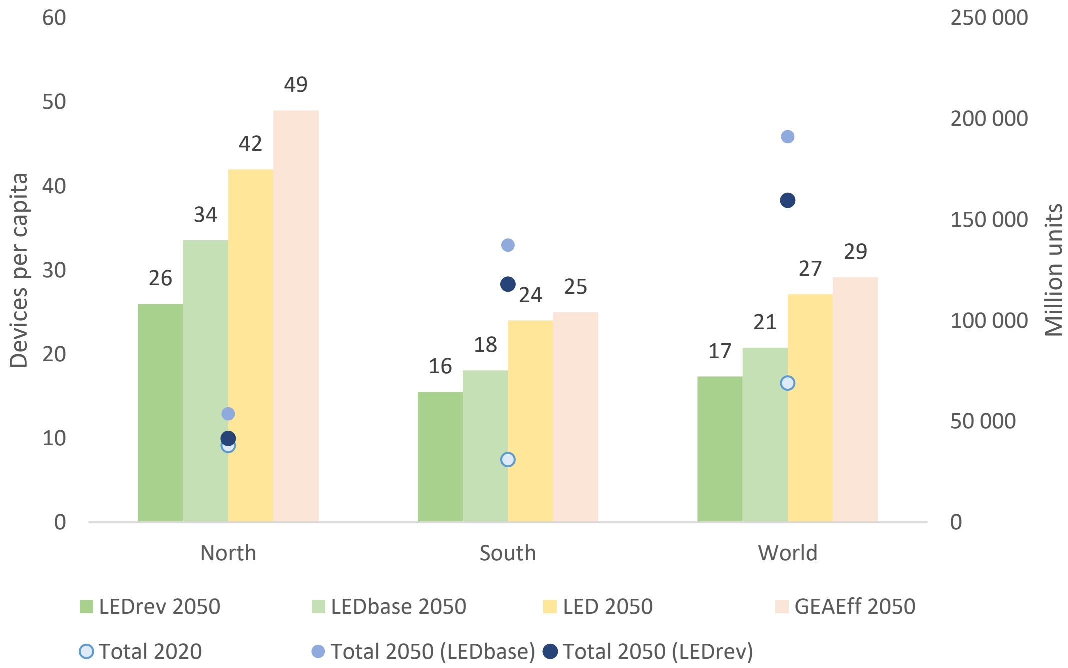


Figure S8. Comparing the number of devices (total and per capita) in 2050 in LEDbase and LEDrev with previous studies (LED and GEA Efficiency).

Figure S8 compares the projections for the number of devices in 2050 in previous studies. LEDbase is already much lower than LED which estimated the number of appliances at 252 billion units in 2050 (blue dots). This is mainly due to a more granular treatment of the number of appliances in the commercial sector (-26 billion units). In addition, by analyzing explicitly a largest set of technologies, we were able to improve the estimation of the residual category “Others” (-41 billion units).

Therefore, the number of devices per capita reduces to 34 in LEDbase, or to 26 per capita when taking into account DLS, digital convergence and sharing, in LEDrev.

Table S7. Increase in the number of devices from 2020 to 2050, by region. (LEDbase at top and LEDrev at bottom)

(LEDbase)

Sector	Category	Appliance	2020	WEU	NAM	PAO	EEU	FSU	SAS	CPA	PAS	LAM	SSA	MEA	2050
Residential	Lighting	Lamps	27631	2477	755	411	500	3014	8358	18091	8254	7391	1432	6883	85194
	Hygiene	Washing machine	1058	30	82	3	4	52	491	253	105	133	195	152	2559
		Water heater	1029	42	71	7	5	56	475	285	117	139	207	180	2613
	Food preparation	Refrigerator	1258	40	76	6	5	47	528	299	104	125	210	151	2849
		Freezer	430	14	98	3	-15	20	140	235	79	79	33	38	1153
		(electric) Stove	549	66	159	18	18	67	200	282	131	144	-11	118	1741
		(electric) oven	185	38	47	11	7	15	71	105	33	36	29	32	607
	Communication & ent	Television	1392	95	170	22	9	29	302	380	177	70	178	123	2946
		Mobile phone	6167	22	55	20	20	-33	376	123	121	90	635	136	7732
		PC (internet access)	1211	216	416	56	65	139	487	1071	343	308	108	256	4675
	Thermal demand	Fan	1239	55	171	14	35	74	130	200	48	164	120	159	2409
		Portable air conditioner	117	21	22	2	3	11	29	39	10	18	13	19	302
	Miscellaneous	Miscellaneous electric loads	3230	440	99	24	48	251	1042	1726	686	691	322	640	9198
Commercial	Lighting	Lamps	18258	-91	990	62	193	1787	6118	10353	5624	5169	235	5296	53994
	Hygiene	Washing machine	53	1	4	0	0	3	25	13	5	7	10	8	128
		Water heater	842	99	129	27	18	44	231	330	99	110	95	100	2125
	Food preparation	Commercial refrigeration	45	6	8	2	1	3	13	20	6	7	6	6	121
		Industrial refrigeration	4	0	1	0	0	0	1	1	0	0	0	0	9
		(electric) Stove	410	69	86	19	12	28	138	203	62	68	56	61	1214
	Communication & ent	Television	1392	95	170	22	9	29	302	380	177	70	178	123	2946
		PC (internet access)	1163	148	349	37	52	154	438	839	269	168	70	251	3936
	Thermal demand	Fan	1239	55	171	14	35	74	130	200	48	164	120	159	2409
		Portable air conditioner	29	4	3	0	0	2	5	6	1	3	2	4	60
	Productive uses	Power in agriculture, fishery,	59	7	9	2	1	3	16	24	8	7	6	7	149
		Heating in agriculture, fishery	13	1	1	0	0	1	1	1	0	1	1	1	20
		TOTAL	69003	3948	4143	780	1025	5869	20044	35457	16507	15165	4247	14902	191092
		Population (millions)	7776	559	453	151	116	277	2373	1408	693	741	1694	704	9169
		units per capita	9	7	9	5	9	21	8	25	24	20	3	21	21

(LEDrev)

Sector	Category	Appliance	2020	WEU	NAM	PAO	EEU	FSU	SAS	CPA	PAS	LAM	SSA	MEA	2050
Residential	Lighting	Lamps	27631	904	-490	-24	181	2341	6756	14570	6788	5826	953	5591	71027
	Hygiene	Washing machine	1058	-171	-104	-52	-33	-29	156	-165	-69	6	223	-21	801
		Water heater	1029	-49	-18	-18	-10	21	395	117	48	117	372	108	2113
	Food preparation	Refrigerator	1258	-4	37	-6	-3	30	433	208	65	139	309	113	2580
		Freezer	430	-9	73	-4	-19	13	113	192	64	63	20	24	960
		(electric) Stove	549	27	115	6	11	55	527	248	143	287	357	162	2487
		(electric) oven	185	26	33	7	5	11	534	412	151	288	415	165	2232
	Communication & ent	Television	1392	-199	-147	-62	-42	-78	-166	-241	-54	-103	59	-87	271
		Mobile phone	6167	22	55	-54	-59	-143	376	300	-169	390	635	-130	7390
		PC (internet access)	1211	-380	-279	-118	-32	-52	-27	-104	-33	-81	282	-60	325
	Thermal demand	Fan	1239	55	171	14	35	74	317	200	48	277	373	172	2975
		Portable air conditioner	117	8	5	-2	1	6	539	418	154	294	418	173	2131
	Miscellaneous	Miscellaneous electric loads	3230	-188	-416	-146	-78	-28	186	206	86	67	22	125	3066
Commercial	Lighting	Lamps	18258	-91	990	62	193	1787	6118	10353	5624	5169	235	5296	53994
	Hygiene	Washing machine	53	1	4	0	0	3	25	13	5	7	10	8	128
		Water heater	842	-120	-119	-37	-18	-30	-42	-115	-54	-49	-14	-32	213
	Food preparation	Commercial refrigeration	45	6	8	2	1	3	13	20	6	7	6	6	121
		Industrial refrigeration	4	0	1	0	0	0	1	1	0	0	0	0	9
		(electric) Stove	410	69	86	19	12	28	138	203	62	68	56	61	1214
	Communication & ent	Television	1392	95	170	22	9	29	302	380	177	70	178	123	2946
		PC (internet access)	1163	-354	-236	-110	-30	-7	-16	-150	-48	-160	-37	-16	0
	Thermal demand	Fan	1239	55	171	14	35	74	130	200	48	164	120	159	2409
		Portable air conditioner	29	-3	-4	-2	-1	0	-3	-7	-3	-1	-1	0	6
	Productive uses	Power in agriculture, fishery,	59	7	9	2	1	3	16	24	8	7	6	7	149
		Heating in agriculture, fishery	13	1	1	0	0	1	1	1	0	1	1	1	20
		TOTAL	69003	-293	117	-488	161	4111	16823	27283	13049	12855	4998	11948	159569
		Population (millions)	7776	559	453	151	116	277	2373	1408	693	741	1694	704	9169
		units per capita	9	-1	0	-3	1	15	7	19	19	17	3	17	17

5. IMPACT ON ENERGY DEMAND

Figure S9 presents the increase in the energy demand from 2020 to 2050. Similarly to Figure S7, we show separately the effects of decent living standards, digital convergence and sharing economies that lowers the energy demand from the scenario LEDbase to LEDrev.

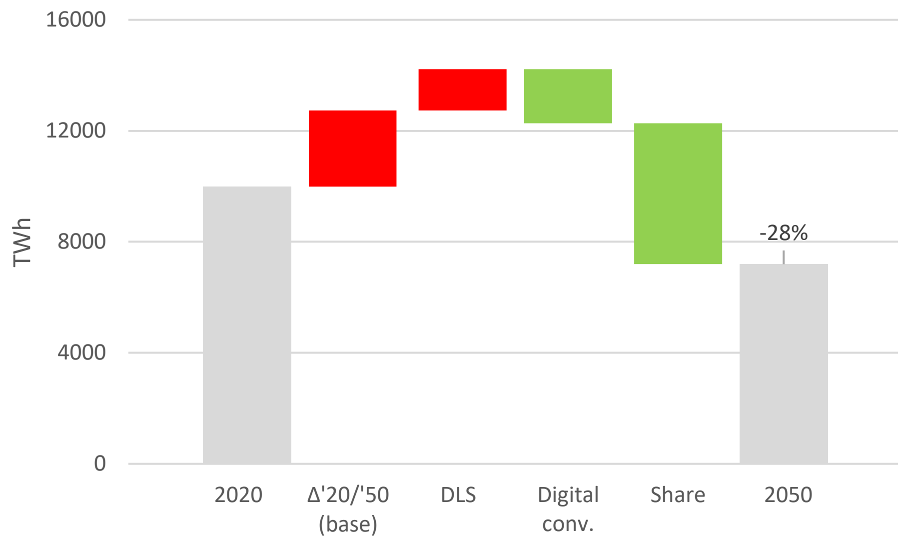


Figure S8. Disaggregation of the growth in the energy demand from consumer goods in 2050 in terms of the increase in the base scenario (LEDbase), decent living standards (DLS), digital convergence and sharing economies (2050=LEDrev).

From right to left, energy demand in LEDbase increases 28% (+2,752 TWh) despite the growth in the number of devices of 177% in 2050. This is due to the trends in energy efficiency which are assumed to be the same as in LED. Ensuring decent living standards increases energy demand by around 1,500 TWh. This would be more than compensated by digital convergence (- 1,952 TWh). Finally, sharing appliances decreases the energy consumption around 5,000 TWh. As a result, the total energy demand in LEDrev falls to 7,194 TWh, 28% below the 2020 levels.

Comparing to LED, energy use changes slightly in 2050 in LEDbase (12,738 TWh instead of 11,477 TWh in LED). Again this results from the more explicit treatment of the consumer goods that were previously considered in the residual category “others”, along with a more detailed analysis of the consumption from appliances in the commercial sector. Energy demand is much lower (7,111 TWh) in the LEDrev scenario.

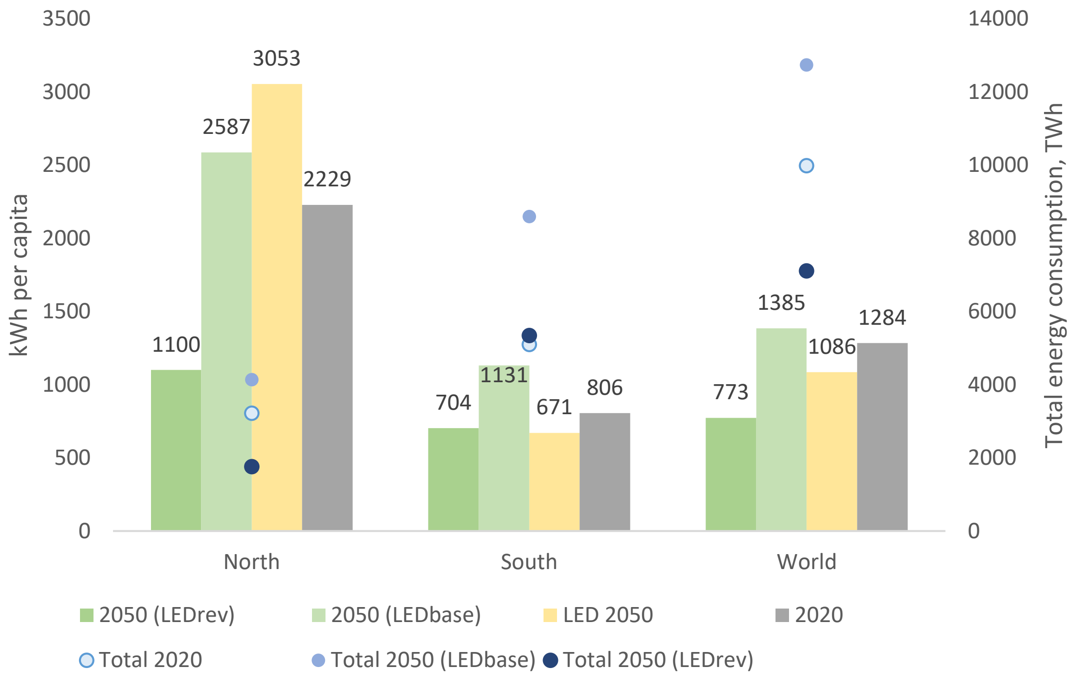


Figure S9. Comparing the energy demand from consumer goods (total and per capita) in LEDbase, LEDrev and LED, by region.

Figure S9 compares the energy consumption, total and per capita, in different scenarios. LEDrev significantly reduces the energy use from appliances, particularly in the Global North where consumption shrinks to a third in comparison to the original LED scenario. Table S6 shows the changes in energy use from 2020 to 2050 under LEDrev, by region and by appliance. Energy use mainly decreases by centralizing equipment as water heaters at the building level, and converging electronics such as PCs, TVs or other peripherals into a smaller number of highly efficient portable devices and all-in-one media stations.

Table S6. Increase in the energy demand from consumer goods from 2020 to 2050 in LEDrev (TWh)

Energy demand TWh (LEDrev)

Sector	Category	Appliance	2020	WEU	NAM	PAO	EEU	FSU	SAS	CPA	PAS	LAM	SSA	MEA	2050
Residential	Lighting	Lamps	356	6	-32	-9	-4	15	42	109	50	30	-3	40	600
	Hygiene	Washing machine	166	-12	-93	-5	-8	-8	2	-1	-10	0	12	-5	39
		Water heater	818	-104	-118	-53	-35	-22	74	-62	-26	-7	83	14	562
	Food preparation	Refrigerator	219	0	-3	-3	-2	-5	51	11	4	18	28	6	324
		Freezer	150	-2	20	-4	-6	-4	26	46	15	17	-1	-1	255
		(electric) Stove	75	-12	-3	-4	-1	2	25	-1	6	14	12	8	121
		(electric) oven	21	-1	-1	0	0	0	20	14	5	11	16	6	90
	Communication & ent	Television	400	-57	-42	-18	-12	-23	-53	-69	-15	-38	-1	-25	46
		Mobile phone	11	0	0	0	0	0	1	1	0	1	1	0	13
		PC (internet access)	112	-35	-26	-11	-3	-5	-3	-10	-3	-8	25	-6	28
	Thermal demand	Fan	86	1	3	-2	1	0	-4	-14	-7	7	9	5	85
		Portable air conditioner	203	13	11	-10	2	11	306	214	77	167	244	101	1338
	Miscellaneous	Miscellaneous electric loads	364	-28	-52	-18	-12	-10	7	-1	0	-4	-2	6	250
Commercial	Lighting	Lamps	695	-48	-86	-21	-11	18	71	136	80	46	-20	75	937
	Hygiene	Washing machine	53	1	-5	0	-1	0	6	13	-3	7	4	2	79
		Water heater	3877	-609	-612	-184	-94	-157	-261	-641	-285	-266	-94	-183	489
	Food preparation	Commercial refrigeration	83	12	7	2	1	0	19	20	8	12	5	5	172
		Industrial refrigeration	513	63	35	10	6	-2	108	112	42	68	28	25	1009
		(electric) Stove	112	-6	-4	-2	-1	-1	7	6	0	1	3	2	118
	Communication & ent	Television	400	-23	-6	-8	-6	-10	25	35	23	-9	19	10	450
		PC (internet access)	216	-66	-44	-20	-6	-1	-3	-28	-9	-30	-7	-3	0
	Thermal demand	Fan	86	1	3	-2	1	0	-11	-14	-7	3	1	5	66
		Portable air conditioner	51	-5	-7	-3	-1	0	-5	-13	-5	-3	-2	-1	6
	Productive uses	Power in agriculture, fishery,	828	-140	-141	-42	-22	-37	-65	-152	-66	-64	-24	-45	29
		Heating in agriculture, fishery	19	-1	-2	-1	0	0	-4	-6	-3	-1	-1	0	0
	Stand by	(all)	76	0	0	0	0	0	0	0	0	0	0	0	2
		TOTAL	9987	-1054	-1198	-408	-215	-236	385	-295	-130	-25	335	40	7110
		Population (millions)	7776	559	453	151	116	277	2373	1408	693	741	1694	704	9169
		kWh per capita	1284												775

6. IMPACT ON MATERIAL CONSUMPTION

The demand for consumer goods that is expected in 2050 have important repercussions in material consumption. The most significant impacts of LEDbase and LEDrev are precisely in lowering these material requirements. Figure S10 shows the changes in material consumption in terms of volume (left-hand) and weight (right-hand).

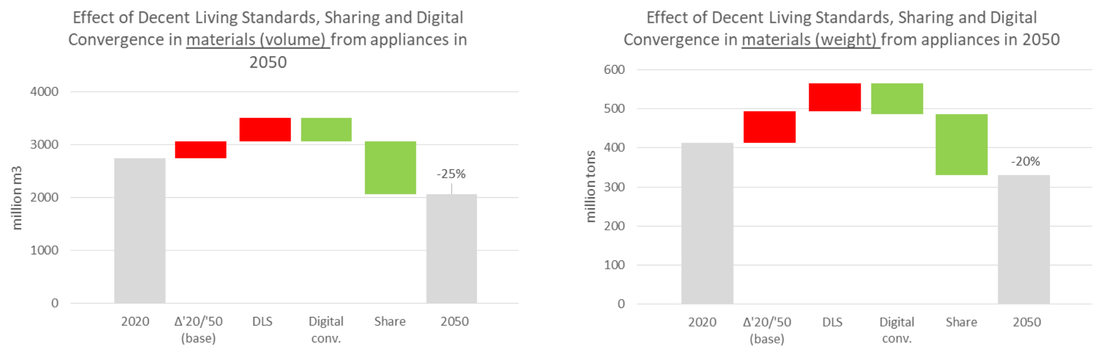


Figure S10. Disaggregation of the material requirements (weight and volume) from consumer goods in 2050 in terms of the effect of growth in the base scenario (LEDbase), decent living standards (DLS), digital convergence and sharing economies (2050=LEDrev).

The material requirements in weight lowers 20% in LEDrev, despite the increase of 137% in the number of appliances in 2050 that is projected in this scenario. Digital convergence (-78 million tons) alone absorbs the growth expected in LEDbase (+80 million tons). Additionally, the material savings from sharing devices would amount to 157 million tons. This is even higher than the projected increase in material consumption in base (LEDbase) and in DLS altogether.

On the other hand, the materials volume lowers 25% assuming the continuation of the observed trends in the relation between size and weight, including downsizing in several objects such as miniaturization in electronics.

Table S7 shows the effect of the estimated demands of consumer goods in 2050 in the consumption of materials (both stock and annual fluxes) by region, comparing to 2020. As for the stock of appliances, most of the reduction in the material requirements come from the Global North where they reduce to almost a third under LEDrev. Material needs per capita lowers in the North to 43 kg in 2050 from 133 kg in 2020.

The annual replacement fluxes, on the other hand, refer to the material consumption needed to produce the consumer goods which substitute those arriving to the end of lifetime. Under the LEDrev scenario, the annual replacement flux reduces from 49 million tons to 32 million tons between 2020 and 2050. Most of the reductions occur in the Global North where the annual flux shrinks to less than a third thanks to digital convergence and sharing, while it remains stable in the Global South in 2050. Therefore material needs lowers to 4 kg per capita in the Global North, comparing to 17 kg per capita in 2020.

Table S8. Material requirements in 2020 and 2050 (LEDbase and LEDrev), by region

	2020			2050 LEDbase			2050 LEDrev		
	Volume (million m3)	Weight (million tons)	kg per capita	Volume (million m3)	Weight (million tons)	kg per capita	Volume (million m3)	Weight (million tons)	kg per capita
Stocks									
World	**2741**	**414**	**53**	**3064**	**494**	**54**	**2063**	**329**	**36**
North	1265	192	133	864	140	87	430	69	43
South	1476	222	35	2200	355	47	1633	261	34
Annual flux									
World	**312**	**49**	**6**	**354**	**59**	**8**	**194**	**32**	**3**
North	151	24	17	100	17	12	44	7	4
South	161	25	4	254	43	7	150	25	3

Table S8 presents the changes in the demand of specific materials for annual replacement of consumer goods under different scenarios. The annual demand of steel, aluminum and plastics in LEDrev reduces to a third in average, despite the double of devices expected for 2050. In comparison, the demand of steel, aluminum and plastics grows 17%, 29% and 23% respectively in the LEDbase scenario, highlighting the importance of digital convergence and sharing to reduce material consumption. A large part of the material savings come from the regions in the Global North (Table S9).

We estimate the embodied energy, i.e. the energy necessary for the raw materials extraction and the manufacturing of the appliances.[13] We calculate the embodied energy by appliance based on the needs for typical models in 2020. Product changes may alter the embodied energy of the appliances in 2050; however the energy intensity may remain similar in 2050 due to the even more sophisticated methods of production and the trend for digitalization of the

[13] We follow a methodology close to:

-Boustani, A., Sahni, S., Graves, S. C., & Gutowski, T. G. (2010, May). Appliance remanufacturing and life cycle energy and economic savings. In *Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology* (pp. 1-6). IEEE;

-and Ciceri, N. D., Gutowski, T. G., & Garetti, M. (2010, May). A tool to estimate materials and manufacturing energy for a product. In Proceedings of the 2010 IEEE international symposium on sustainable systems and technology (pp. 1-6).

devices, with increasing shares of electronics (highly energy intensive). In this context, embodied energy reduces almost 40% in 2050 under the LEDrev scenario, comparing to an increase of 22% in LEDbase. This result stresses again the potential for material savings that can be reached with digital convergence and sharing of devices.

Table S9. Annual replacement flux in 2020 and 2050, by type of material (million tons unless specified otherwise)

	2020	2050 LEDbase	Δ% to 2020	2050 LEDrev	Δ% to 2020
Total weight	**49**	**59**	**20%**	**32**	**-35%**
Steel	23	27	17%	15	-33%
Aluminum	2	3	29%	2	-38%
Plastic	11	13	23%	8	-26%
Embodied (TJ)	**4459**	**5445**	**22%**	**2724**	**-39%**

Table S10. Comparing the annual material flows (in million tons) associated to the replacement of old consumer goods in 2020 and 2050 under LEDrev, by region

Annual replacement flows in million tons (LEDrev)

Sector	Category	Appliance	2020	WEU	NAM	PAO	EEU	FSU	SAS	CPA	PAS	LAM	SSA	MEA	2050
Residential	Lighting	Lamps	1	-0,11	-0,12	-0,04	-0,02	-0,01	0,01	0,02	0,03	0,00	-0,02	0,02	0
	Hygiene	Washing machine	4	-0,68	-0,42	-0,20	-0,13	-0,14	0,17	-0,83	-0,35	-0,20	0,27	-0,15	1
		Water heater	3	-0,42	-0,28	-0,13	-0,09	-0,04	0,58	-0,25	-0,11	0,02	0,61	0,12	4
	Food preparation	Refrigerator	7	-0,56	-0,29	-0,18	-0,12	-0,08	0,93	-0,19	-0,20	0,01	0,61	0,08	7
		Freezer	1	-0,14	0,03	-0,04	-0,06	-0,01	0,09	0,17	0,05	0,05	-0,02	-0,02	1
		(electric) Stove	0	-0,02	0,00	0,00	0,00	0,01	0,06	0,01	0,02	0,03	0,03	0,02	0
		(electric) oven	0	0,00	0,00	0,00	0,00	0,00	0,08	0,06	0,02	0,04	0,06	0,02	0
	Communication & ent	Television	2	-0,25	-0,18	-0,08	-0,05	-0,10	-0,24	-0,30	-0,07	-0,18	-0,04	-0,11	0
		Mobile phone	0	0,00	0,00	0,00	0,00	-0,01	0,02	0,02	-0,01	0,03	0,04	-0,01	1
		PC (internet access)	2	-0,56	-0,41	-0,17	-0,05	-0,08	-0,06	-0,15	-0,05	-0,12	0,15	-0,09	0
	Thermal demand	Fan	0	0,01	0,03	0,00	0,00	0,01	0,00	-0,01	-0,01	0,01	0,01	0,01	0
		Portable air conditioner	0	0,02	0,02	-0,02	0,00	0,02	0,69	0,50	0,18	0,38	0,55	0,23	3
	Miscellaneous	Miscellaneous electric loads	17	-1,80	-2,82	-0,98	-0,56	-0,51	-0,17	-0,94	-0,34	-0,48	-0,28	-0,03	8
Commercial	Lighting	Lamps	0	-0,10	-0,05	-0,02	-0,01	0,00	0,02	0,01	0,02	0,01	-0,01	0,02	0
	Hygiene	Washing machine	2	-0,19	-0,05	-0,06	-0,04	0,01	0,50	-0,03	-0,01	0,03	0,18	0,10	3
		Water heater	4	-0,65	-0,65	-0,20	-0,10	-0,17	-0,28	-0,68	-0,30	-0,28	-0,10	-0,20	1
	Food preparation	Commercial refrigeration	0	-0,01	0,00	0,00	0,00	0,00	0,03	0,04	0,01	0,01	0,01	0,01	0
		Industrial refrigeration	0	0,01	0,00	0,00	0,00	0,00	0,01	0,02	0,01	0,01	0,00	0,00	0
		(electric) Stove	1	0,00	0,01	0,00	0,00	0,01	0,07	0,08	0,02	0,02	0,03	0,02	1
	Communication & ent	Television	2	-0,14	-0,07	-0,05	-0,03	-0,06	0,00	0,02	0,05	-0,09	0,02	0,00	1
		PC (internet access)	2	-0,52	-0,35	-0,16	-0,04	-0,01	-0,02	-0,22	-0,07	-0,23	-0,05	-0,02	0
	Thermal demand	Fan	0	0,01	0,03	0,00	0,00	0,01	-0,01	-0,01	-0,01	0,01	0,00	0,01	0
		Portable air conditioner	0	-0,01	-0,01	-0,01	0,00	0,00	-0,01	-0,02	-0,01	-0,01	0,00	0,00	0
	Productive uses	Power in agriculture, fishery,	1	-0,11	-0,10	-0,03	-0,02	-0,03	-0,05	-0,11	-0,05	-0,05	-0,02	-0,03	0
		Heating in agriculture, fishery	0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0
		TOTAL	49	-6	-6	-2	-1	-1	2	-3	-1	-1	2	0	32
		Population (millions)	7776	559	453	151	116	277	2373	1408	693	741	1694	704	9169
		kg per capita	6												3

7. ALTERNATIVE SCENARIOS TO REDUCE MATERIAL FLOWS

We consider two sensitive scenarios regarding LEDrev. The first refers to an accelerated trend of reduction in the weight of appliances. The second sensitive scenario assesses the impact on annual material flows of a 25% extension of the appliances' lifetime.

7.1. Lightweight: accelerated reduction of appliances weight

We perform a sensitivity scenario assuming a higher reduction in the material requirements of the appliances than in LEDrev. More precisely, we assess the effect of the reduction to a third the average material weight of the appliances in 2050. This is around a third less than in LEDrev, following the expected reduction in the wattage of the devices to improve their energy efficiency.

Figure S11 shows the annual material flux in the lightweight sensitivity scenario (LEDrev-LW) and in the other scenarios. It is worthwhile to remember that the lightweight scenario is estimated on top of LEDrev, assuming the same increase in the number of appliances in 2050 (+137%), but only changing the material intensity (kg per unit) of the devices. Comparing to LEDrev, the accelerated reduction of unit weight in LEDrev-LW significantly lowers the total weight of appliances relatively to 2020 in -54%, instead of -35%. The highest reductions occur in the consumption of aluminum (-57%) in relative terms, and of steel (less 11 million tons) in absolute terms. These numbers are significantly lower than in LEDbase which projects an increase in the consumption of the materials under analysis.

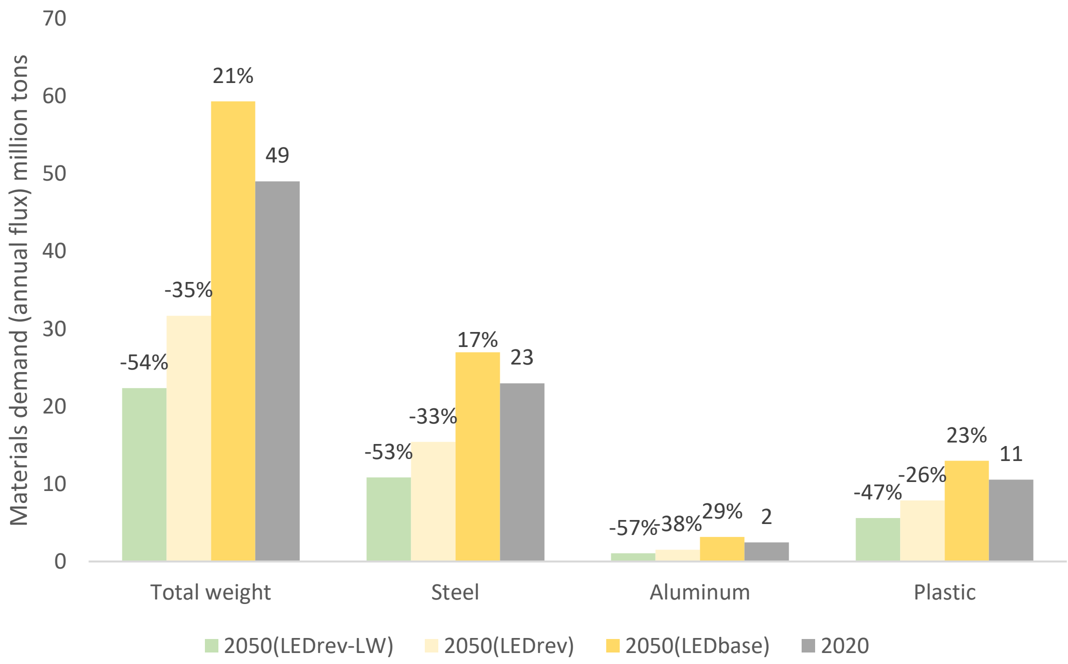


Figure S11. Comparing the annual material flux in 2020 with 2050 in LEDbase, LEDrev and LEDrev with a lightweight scenario (LEDrev-LW)

7.2. Lifetime extension

The second sensitivity analysis examines the effect of assuming a 25% extension of the lifetime of the appliances in the annual material fluxes. Lifetime extension should be less technically demanding comparing to lightweight which would require the introduction of new product architectures, production methods, and new materials that are even lighter than in LEDrev with similar robustness.

Extending the lifetime of the products entails a change in the marketing strategy of companies. These should move away from the well documented practices of programmed obsolescence, consisting of product design, manufacturing and marketing that artificially limit their useful live to accelerate the rates of replacement. Already in 1960, Vance Packard denounced some marketing strategies followed by companies to provoke artificial obsolescence through constant modernization of the models, lowering quality or fashion (Packard & McKibben, 1963). Nowadays there are laws in several countries (e.g. France) that prevent programmed obsolescence, but their enforcement remains complex.

The analysis shows that lifetime extension has an effect similar to lightweight in reducing the annual material demand (Figure S12). Enlarging the useful life of appliances in 25% — e.g. 20 years instead of 15 for the assumed lifetime of washing machines in 2050, scenario LEDrev-LTX—further reduces the total weight of consumer goods to -48% from -35% in LEDrev. The difference is relatively larger in plastics (-40% from -26% in LEDrev). Lifetime extension halves aluminum consumption comparing to current levels, and reduces the needs in steel in 3 million tons annually.

Considering the lifetime extension on top of the lightweight assumption, the scenario LEDrev-LW-LTX, reduces even further the material consumption of appliances. The consumption of steel, aluminum or plastics is almost cut by a half comparing to LEDrev. These results show the importance of considering the two measures, lifetime extension and material intensity reduction (lightweight), together to accelerate dematerialization in consumer goods.

These estimations assume that the share of the materials in the manufacturing of the devices remains the same in 2050. However, lifetime extension may have implications in the choice of the materials used in device manufacturing, as well as in the share of these materials. We recognize this limitation but considering the high levels of uncertainty about the manufacturing of products in 2050, it is more transparent to assume that the relative share of materials in production would not significantly change in the future. Therefore our estimations should be considered under that assumption.

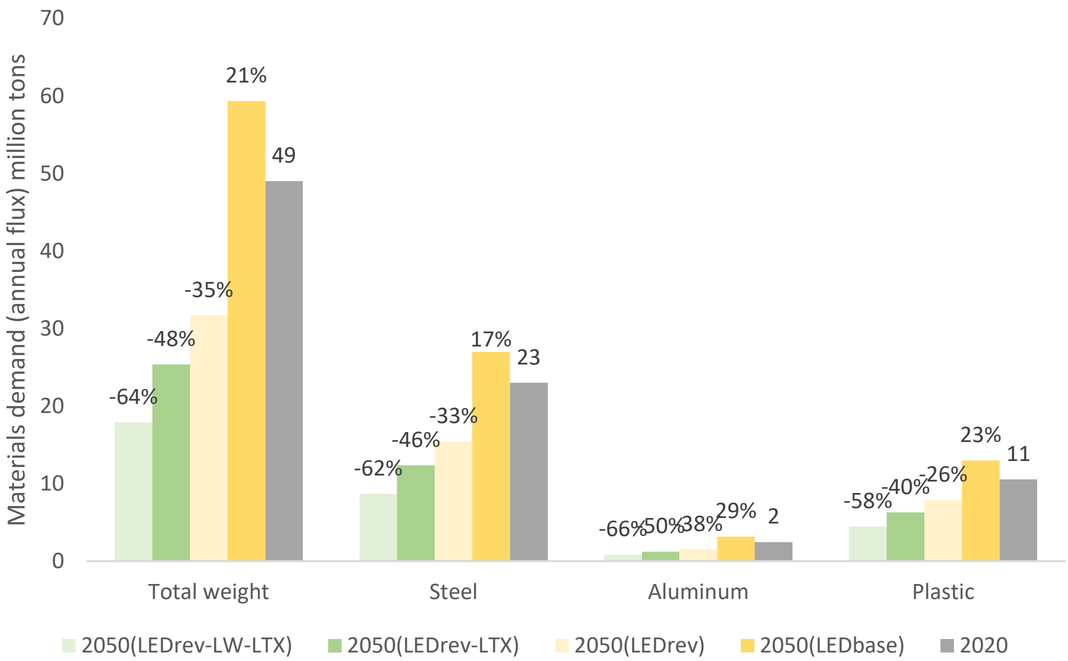


Figure S12. Comparing the annual material flux in 2020 with 2050 in LEDbase, LEDrev and LEDrev with a lifetime extension scenario (LEDrev-LTX) and the latter on top of the scenario assuming lightweight (LEDrev-LW-LTX)

8. CONCLUSION

In the face of a rapid growth in the demand of consumer goods that increases the pressure in materials consumption and puts at risk the efforts of decarbonization, strategies are needed to lower the environmental footprint of appliances in a way that achieves the 1.5ºC target in 2050 and enables access to modern services provided by consumer goods to the population in the Global South. The publication of the LED study in 2018 already advanced in the understanding of the effects of the rising demand for consumer goods and of the measures that could make it compatible with the needs of sustainable development.

Meanwhile the trends in the energy demand from appliances have accelerated (IEA, 2020), along with the signs of climate deregulation that brought the UN secretary general to urge the countries to declare a state of climate emergency. The pandemic did not put away the perception of the climate urgency, but rather accelerated some of the observed trends towards digitalization and the development of social innovations and new forms of organization of service provision (teleworking, online media, etc.) (Kikstra et al., 2021).

Therefore, there is the need for a finer-grain analysis, both spatially and by more type of products, to better understand the factors that drive the growth of energy demand and material consumption in appliances in order to design strategies to reduce them in line with the needs of decarbonization.

This study addresses this need by developing a more disaggregated analysis of the demand for consumer goods, now and in 2050, considering explicitly 11 regions instead of 2 in LED, and a larger range of consumer goods, including in the commercial sector. Additionally, this research aims to understand the potential of digital convergence and sharing for the decarbonization and the dematerialization of consumer goods.

We have re-estimated the previous LED scenario with the most up-to-date information on appliances demand and efficiency. This LEDbase scenario was then compared to a revised scenario (LEDrev) which includes the needs for ensuring decent living standards for all, as well as the savings enabled by digital convergence and sharing.

Table S10 shows the main results from the key scenario (LEDrev). The main outcomes are summarized as following:

- between 2020 and 2050, the number of appliances more than double in LEDrev while the population increases 18% in the same period, hence doubling the number of devices per capita (mainly in the Global South);

- energy demand reduces around a third in the same period, benefiting from efficiency improvements that reduces the energy intensity of the devices to a third of the levels in 2020;
- the material consumption lowers 20% thanks to the division by three of the material intensity of the devices.

Table S11. Decomposition analysis: Base case (LEDbase) with decent living standards, digital convergence and sharing (LEDrev)

	(1)	(2)	(3)	(4)			
	Number of appliances	**Energy demand**	**Material consumption**	**Population**	**Devices per cap**	**Energy intensity**	**Material intensity**
	(millions)	(TWh)	(million kg)	(millions)	(4)/(2)	(2)/(1)	(3)/(1)
2020	69,003	9,987	414	7,776	8.9	0.145	0.006
2050	159,569	7,111	329	9,169	17.4	0.045	0.002
cagr	2.8%	-1.1%	-0.8%	0.6%	2.3%	-3.9%	-3.5%
2050/2020	**2.31**	**0.71**	**0.80**	**1.18**	**1.96**	**0.31**	**0.34**

A more in-depth analysis of the energy intensity distinguishes the effect of the change in the weights of the categories of appliances (structural effect) from the improvement of intensity within the categories.

Structural change amplifies the effects of efficiency improvement. By reducing the weight of large, more energy intensive, devices, digital convergence and sharing contributes to lower the overall energy demand from appliances (Figure S13). The structural effect alone reduces 40% (the reverse of the multiplier 1.89) the energy demand, comparing with the hypothetical situation under which the basket of consumer goods remains unchanged between 2020 and 2050. Accounting for the structural effect is important as, in the extreme case, it could explain the paradox under which the overall energy demand from consumer goods would reduce even if the consumption within a large number of categories increases (namely due to the democratization of their use). The structural effect also explains the feasibility of deep reductions in energy demand (and thus carbon emissions) without assuming unprecedent rates of efficiency improvement.

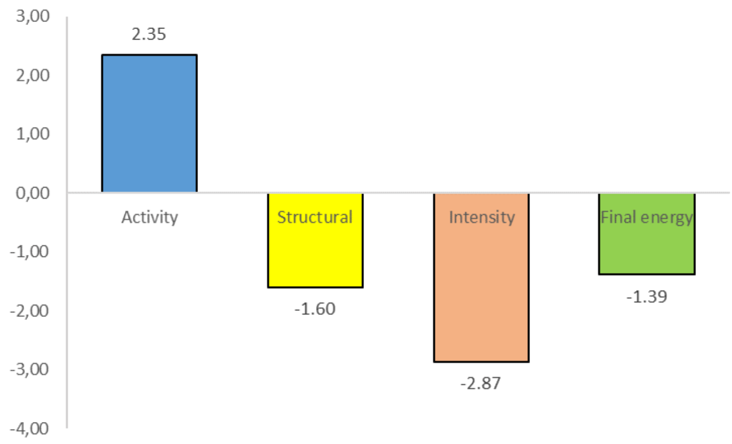


Figure S13. Disaggregation analysis: 2020-2050 multiplier/divisor. Changes in 2020–2050 in total global activity, structure of goods, energy intensity and final energy demand. Multiplier or divisor depending on the number being positive or negative.

Table S11 compares the outcomes of the different scenarios. These are the main highlights:

- comparing to the previous LED study, the number of devices estimated for 2020 are much lower, particularly in the Global South;
- LEDrev projects a lower number of devices in 2050, and a much lower energy use in 2050, due to a more detailed analysis by category of appliances;
- the difference between the estimations in LEDrev and LEDbase (which updates LED with new information and a finer-grain disaggregation by region and by appliances) roughly corresponds to the potential of digital convergence and sharing to lower carbon emissions from appliances: these two processes can more than compensate the increase in the number of devices due to ensuring decent living standards for all; while still lowering the number of devices in 2050 from 191 billion units to around 160 billion, reducing 44% the energy demand to 7,111 TWh and halving the material weight for annual replacement from 59 tons to 32 tons;
- the cost of the 30 million units saved through digital convergence and sharing in LEDrev correspond to 9 trillion US dollars at the current prices (using the price in global outlets, e.g. Amazon, of representative items of each category).

Table S12. Comparison of scenarios

	2020 LED	2050 LED	2020 LEDbase	2050 LEDbase	2050 LEDrev
Million units					
World	105,034	252,751	69,003	191,092	159,569
North	37,582	67,097	37,986	53,751	41,595
South	67,452	185,654	31,017	137,341	117,974
TWh					
World	9,987	11,477	9,987	12,738	7,111
North	4,885	3,643	4,908	4,139	1,760
South	5,102	7,834	5,079	8,599	5,351
Million tons (annual replacement)					
World	-	-	48	59	32
North	-	-	23	17	7
South	-	-	24	43	25

The results have several implications for policy and for research. As for policy, special attention should be given to the appliances with the highest energy consumption (portable air conditioners, refrigerators, water heaters, commercial and industrial refrigeration, etc.). It is particularly important to follow the growth in the demand for consumer goods in the Global South, and understand to what extent the population from this region can enjoy from efficiency improvements through, e.g., a wider dissemination of efficiency standards. Policies that phase out inefficient models have been effective particularly when there is an affordable alternative like in the case of phasing out incandescent light bulbs in lighting (e.g., Zissis & Bertoldi, 2018). On the other hand, policy could promote the sharing of equipment (air conditioner, ventilation, water heating, washing machines, tools, etc.) at the building level by removing legal and regulatory barriers or using instruments such as incentives or minimum requirements. Policymakers could also stimulate digital convergence of the devices by taking into account multi-functionality in the definition of efficiency standards or by supporting R&D partnerships on new converging devices following the model of development of LED lights in the past (DOE, 2012).

As for research, this study reveals promising directions to orient the efforts of the science and technology community to raise sustainability in consumer goods. On the one hand, the results point to key technical challenges that need further refinements and improvements in the coming years. For example, these efforts could focus on efficiency improvements, introduction of lightweight materials, development of product architectures enabling sharing and longer product lifetimes. On the other hand, the study shows the impact of possible discontinuities in the pursuit of the current technological trends. The ongoing digitalization of the objects opens new possibilities for improving energy efficiency and the provision of new services (e.g. smart refrigerators which automatically order food). But the digitalization also accelerates the convergence between objects going up to substituting the physical devices (e.g. smartphones substituting the second TV set, DVD players, radios, …).

There are some limitations in our estimations. Firstly, we identify sharing potential by assuming the more widespread dissemination of localized practices (washing machines rooms at the building level in North America, student residences and co-living places for young and elderly in the Global North, etc.). More research is needed involving different perspectives (sociological, demographics, economics, etc.) on the potential for dissemination of these and other practices involving different segments of the population (single adults, monoparental families, etc.). Similarly, more studies are needed on the impacts of the digitalization of consumer goods and services. This assumes multiple ways (including connecting with other sectors like foods and transports) and can increase emissions in some applications (Wilson et al., 2020). Secondly, we took efficiency trends from LED and updated them with the most recent data to 2020. These data considers the long-term improvements in efficiency, but there are several accounts that the dynamics have slowed down in the past years (IEA, 2020; Rousselot & Rocha, 2020). More research is needed to understand the reasons of this slowdown (consumer preference changes for larger devices, limits in the current product architectures, etc.) and the impact on the long-term assumptions for efficiency improvement. Finally, the estimates for material intensity and embodied energy base on numbers that are available in the literature and typical models of each category. High uncertainties remain about these values for specific regions, as well as for their evolution in the future with the introduction of both substantially different devices and new ones. These limitations point to relevant avenues for future research.

Appendix 1. Definition for the different levels of spatial disaggregation (Source: GEA, 2012).

Disaggregation on 2 regions *(e.g. LED scenario in Grubler et al., 2018)*	**Disaggregation on 5 regions** *(e.g. LED scenario in the 2019 version)*	**Disaggregatº on 11 regions** *(proposed now)*
Global North: Industrialized countries, i.e. OECD 90 and reforming economies. **Global South:** Developing countries, i.e. Middle East and Africa, Asia and Latin America and the Caribbean regions.	**OECD 90:** Countries that were OECD members in 1990, i.e. Western Europe, North America and Pacific OECD regions. **Reforming Economies (REF)**: Countries of Central and Eastern Europe and the Former Soviet Union undergoing economic reform. **Asia:** South Asia, Centrally planned Asia and China and Other Pacific Asia regions. **Middle East and Africa (MEA):** African and Middle Eastern countries that make up the Sub-Saharan Africa and Middle East and North Africa regions. **Latin America and the Caribbean (LAM):** Latin America and the Caribbean region.	**Sub-Saharan Africa (SSA)** **Centrally planned Asia and China (CPA)** **Central and Eastern Europe (EEU)** **Former Soviet Union (FSU)** **Latin America and the Caribbean (LAM)** **Middle East and North Africa (MEA)** **North America (NAM)** **Pacific OECD (PAO)** **Other Pacific Asia (PAS)** **South Asia (SAS)** **Western Europe (WEU)**

Appendix 2. Best fits of the correlations between number of devices per 100 persons (ownership) and GDP PPP per capita, in 2020, used to estimate the average ownership by device, by region, in 2050.

Lighting	*Type*	Fit Type	R2	a	b	t(max)
Residential	Lamps	logistics	96%	1593	0,000153	24876
Commercial	Lamps	logistics	92%	920	0,000247	21071
Hygiene	*Type*	Fit Type	R2	a	b	t(max)
Residential	Washing machines	logarithmic	86%	15	-125,22	
Residential	Water heaters	logarithmic	88%	16,55	-140,45	
Commercial	Washing machines	logarithmic	86%	7,50E-01	-6,261	
Commercial	Water heaters	linear	100%	0,0007	-2E-14	
Food preparation	*Type*	Fit Type	R2	a	b	t(max)
Residential	Refrigerator	logarithmic	98%	15,127	-123,35	
Residential	Freezer	potential	53%	0,0006	0,9568	
Residential	Stove	linear	77%	0,0007	-4,188	
Residential	Oven	linear	100%	0,0002	-4E-15	
Commercial	Commercial refrigeration	linear	100%	0,00004	1E-15	
Commercial	Stove	linear	100%	0,0004	4E-15	
Commercial	Industrial refrigeration	linear	100%	0,000003	4E-17	
Communication & entertainment	*Type*	Fit Type	R2	a	b	t(max)
Residential	Mobile phone	logarithmic	19%	5,65	26,653	
Residential	PC internet access	linear	89%	0,0019	-11,917	
Residential	Television	linear	77%	0,0007	8,957	
Commercial	PC internet access	linear	82%	0,0016	-10,045	
Commercial	Television	linear	77%	0,0007	8,957	
Thermal demand	*Type*	Fit Type	R2	a	b	t(max)
Residential	Fan	linear	55%	0,0007	3,0981	
Residential	Portable AC	linear	74%	0,0001	-0,017	
Commercial	Fan	linear	55%	0,0007	3,0981	
Commercial	Portable AC	linear	74%	0,00002	-0,0043	
Miscellaneous	*Type*	Fit Type	R2	a	b	t(max)
Residential	Misc	logistics	91%	171	0,000116	24863
Commercial	Power	linear	99%	0,00005	-0,0262	
Commercial	Heating	linear	39%	0,000005	0,0545	

The letters “a” and “b” refer to the parameters of the type of equations used in the best fits. For instance, a linear equation is $y=\boldsymbol{a}x+\boldsymbol{b}$ and a potential equation would be defined as $y=\boldsymbol{a}.x^{\boldsymbol{b}}$. The parameter “t(max)” refer to the third element of a 3 parameters logistic equation: $y=\boldsymbol{a}/(1+exp(-\boldsymbol{b}(x-\boldsymbol{t(max)}))$), where “a” also indicates the saturation level and “t(max)” gives the level of revenue for which device ownership increases at its maximum rate.

Appendix 3. Services provided by appliances in 2020.

Sector	Category	Appliance	Number of devices	Service indicator	Service value
Residential	Lighting	Lamps	27631	billion lumens	18321
	Hygiene	Washing machine	1058	thousand tons of laundry washed	838
		Water heater	1029	trillion liters	31
	Food preparation	Refrigerator	1258	million cooled liters	372
		Freezer	430	million cooled liters	216
		(electric) Stove	549	billion BTUs/h	349942
		(electric) oven	185	billion BTUs/h	270112
	Communication & entertainment	Television	1392	billion hours	2032
		Mobile phone	6167	billion hours of talk	7840
		Mobile phone		billion hours of web browser	3766
		Mobile phone		billion hours of video watching	3766
		Mobile phone		GWh of standby	10191
		PC (internet access)	1211	billion hours	972
	Thermal demand	Fan	1239	billion m3/minute	157043
		Portable air conditioner	117	billion BTU	692804
	Miscellaneous	Electric loads: set-top boxes, rooters, etc.	3230	billion hours	443
Commercial	Lighting	Lamps	18258	billion lumens	27926
	Hygiene	Washing machine	53	thousand tons of laundry washed	1270
		Water heater	842	trillion liters	620
	Food preparation	Commercial refrigeration	45	billion BTU/h	32
		Industrial refrigeration	4	billion BTU/h	200
		(electric) Stove	410	billion BTUs/h	523177
	Communication & entertainment	Television	1392	billion hours	2032
		PC (internet access)	1163	billion units	1868
	Thermal demand	Fan	1239	billion m3/minute	157043
		Portable air conditioner	29	billion BTU	173201
	Productive uses	Power in agriculture, fishery, etc.	59	billion of hours	85
		Heating in agriculture, fishery, etc.	13	billion of hours	20
		Total	**69003**		

Appendix 4. Main inputs used in the analysis of the material requirements of the appliances

Category	Appliance	Steel (%)	Aluminium (%)	Plastic (%)	Mass (kg)	MJ/kg(raw)	MJ/kg(manuf.)	MJ/kg	Notes
Lighting	Lamps	0%	11%	10%	0,101	37	17	54	Babbitt et al., 2017
Hygiene	Washing machine	73%	5%	18%	60	46	17	63	Boustani et al., 2010
	Water heater	77%	2%	11%	30	39	19	58	Kemna et al., 2007
Food preparation	Refrigerator	56%	3%	28%	84	50	17	67	Boustani et al., 2010
	Freezer	0,28	9%	17%	69	78	12	90	assumed the same as small commercial freezers (equiv
	(electric) Stove					34	17	51	assumed the same as for domestic ovens (MJ/kg)
	(electric) oven	78%	5%	2%	28	34	17	51	Reale et al., 2019
Communication & en	Television	60%	0%	20%	12	39	98	137	Stobbe (2007)
	Mobile phone	26%	0%	39%	8	51	51	102	Babbitt et al., 2017
	PC (internet access)	12%	11%	27%	2	79	79	158	laptop
Thermal demand	Fan	24%	7%	34%	5	84	19	103	BRE, 2009
	Portable air conditione	35%	6%	61%	29	101	20	121	Room AC (smaller 7000 BTUs)
Miscellaneous	Small electric load devi	26%	8%	26%	8	56	56	112	Babbitt et al., 2017
Lighting	Lamps	0%	11%	10%	0,101	37	17	54	assumed similar to domestic lamps
Hygiene	Washing machine	73%	5%	18%	60	46	17	63	assumed similar to domestic washers
	Water heater	77%	2%	11%	30	39	19	58	Kemna et al., 2007
Food preparation	Commercial refrigerati	58%	5%	12%	119	42	14	55	Bio Intelligence Service, 2011
	Industrial refrigeration	28%	9%	17%	69	78	12	90	assumed similar to small commercial freezers (equival
	(electric) Stove	77%	3%	7%	136	34	15	49	Bio Intelligence Service, 2011
Communication & en	Television	60%	0%	20%	12	39	98	137	Stobbe (2007)
	PC (internet access)	43%	2%	16%	19	45	45	90	desktop+LED display
Thermal demand	Fan	24%	7%	34%	5	84	19	103	BRE, 2009
	Portable air conditione	35%	6%	61%	29	101	20	121	Room AC (smaller 7000 BTUs)
Productive uses	Power in agriculture, fis	29%	0%	24%	0,25	105	15	120	Rota, 2020
	Heating in agriculture, fishery, etc.					101	20	121	assume similar intensity as portable AC

Sources (Appendix 4):

Babbitt, C.W., Althaf, S., and Chen R. (2017). Sustainable Materials Management for the Evolving Consumer Technology Ecosystem. Available at: https://www.rit.edu/gis/ssil/docs/Final%20Report%20SMM%20Phase%201%202017.pdf. Accessed January 14, 2021.

Boustani, A., Sahni, S., Gutowski, T., & Graves, S. (2010). Appliance remanufacturing and energy savings. Management. http://web.mit.edu/ebm/www/Publications/MITEI-1-a-2010.pdf pages 14-15, 61

Kemna, R., Van Elburg, M., Li, W., & van Holsteijn, R. (2007). Eco-design of water heaters. Draft reports of tasks, 1-5.

Reale, F, Castellani, V, Hischier, R, Corrado, S, Sala, S,Consumer Footprint -Basket of Products indicator on Household appliances,EUR 29758 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-05003-2, doi:10.2760/964701, JRC116704.

Stobbe, L. (2007). EuP Preparatory Studies "Televisions" (Lot 5) -Final Report on Task 4 "Technical Analysis". Berlin (Germany), Fraunhofer Institute for Reliability and Microintegration.

BRE, U. (2009). Preparatory study on the environmental performance of residential room conditioning appliances (airco and ventilation). Policy.

Bio Intelligence Service (2007), Preparatory Studies for Eco-design Requirements of EuPs, Lot 12: Commercial refrigerators and freezers, Final Report, DG TREN, December. Table 257.

Rota (2020). Workpro Drill LCA findings, https://rotaaustralia.weebly.com/research-report.html (assessed 18/1/2021)

Appendix 5. Data available in a separated Excel spreadsheet

The final spreadsheet will become available with detailed information about the assumptions and the results for the different scenarios. It will include an interface in which users can parameterize the main variables, and see the impact on the energy demand from consumer goods in 2050 (Figure S13). The interface will enable the parameterization of the DLS in terms of the number of devices per capita (or by household). Users could also define the maximum potential for digital convergence and sharing economy to respectively lower the energy intensity and the number of devices (Table S12).

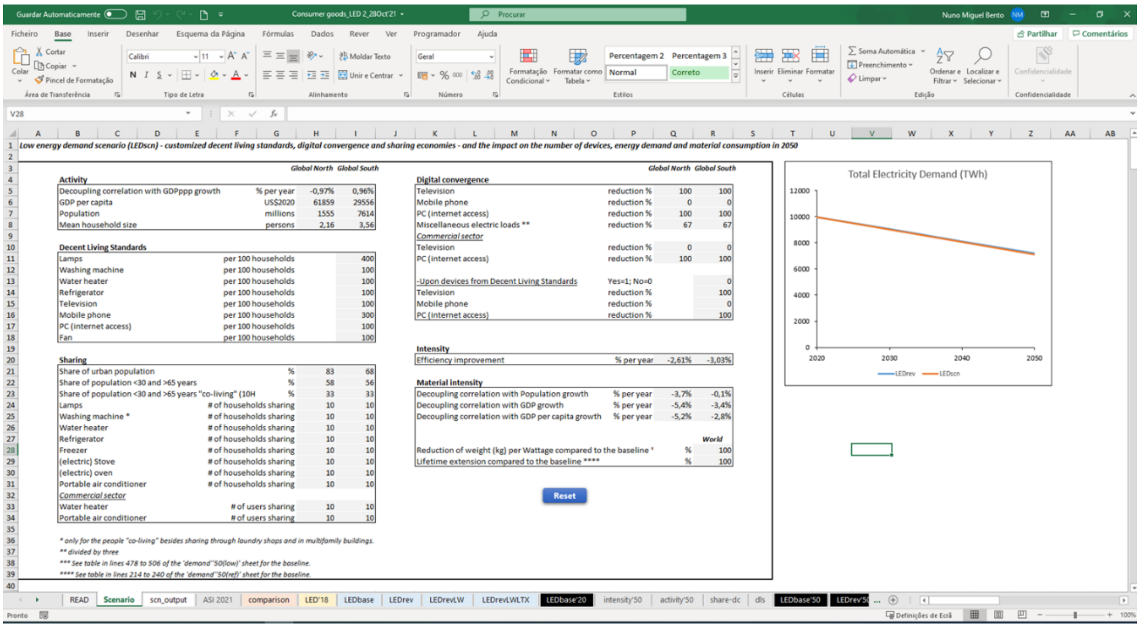


Figure S13. Interface of scenario generator featuring parameterizable key variables.

Table S13. Options to parameterize decent living standards, digital convergence and sharing economy in the interface

Categories of consumer goods	Decent Living Standards	Sharing economy**	Digital convergence***
Lighting	Number of lamps*	n.a.	n.a.
Hygiene	n.a.	Maximum potential for sharing washing machines, water heaters, dishwashers	n.a.
Food preparation	Number of refrigerators*, stoves*	Maximum potential for sharing stoves, refrigerators	n.a.
Communication and entertainment	Number of televisions*, PCs*, mobile phones	Maximum potential for sharing televisions, PCs	Maximum potential for digital convergence of television, mobile phone, PC (or internet device)
Thermal demand	n.a.		
Small electric load devices	n.a.		

* by household (HH), otherwise the number is per person.

** impacts mainly number of devices. Maximum potential for sharing is constrained (i.e. upper bounded) by the share of urban population living in multifamily dwelling, particularly in highly densified megacities.

*** impacts number of devices and energy intensity per device.

n.a.: not applicable.

REFERENCES

ADEME (2019). Modélisation et évaluation environnementale de produits de consommation et biens d'équipement. Rapport RDC Environment, Décembre, 180 pages.

Bainbridge, W. S., & Roco, M. C. (Eds.). (2016). Handbook of Science and Technology Convergence. Switzerland: Springer International Publishing.

Bento, N. (2016). Calling for change? Innovation, diffusion, and the energy impacts of global mobile telephony. Energy Research & Social Science, 21, 84-100.

Bradley, G. (2017). The good ICT society: From theory to actions (Vol. 20). Taylor & Francis.

Brennen, J. S., & Kreiss, D. (2016). Digitalization. *The International Encyclopedia of Communication Theory and Philosophy*, 1-11.

CBRE (2020). Europe Co-living Report. CBRE EMEA Research Team, www. cbre.com/research-and-reports.

DOE (2012). Solid-state lighting research and development: Multi-year program plan. Lighting research and development building technologies program, U.S. Department of Energy.

Enerdata (2020). Energy efficiency trends in buildings in the EU. Odyssee-Mure webinar series on Energy Efficiency organised by Leonardo ENERGY. December 8th, 2020.

Fremstad, A., Underwood, A., & Zahran, S. (2018). The environmental impact of sharing: household and urban economies in CO2 emissions. Ecological economics, 145, 137-147.

Gartner (2021). Digitalization. https://www.gartner.com/en/information-technology/glossary/digitalization (last access 4/3/2021)

Gertler, P. J., Shelef, O., Wolfram, C. D., & Fuchs, A. (2016). The demand for energy-using assets among the world's rising middle classes. American Economic Review, 106(6), 1366-1401.

Gill, B., & Moeller, S. (2018). GHG emissions and the rural-urban divide. A carbon footprint analysis based on the German official income and expenditure survey. Ecological Economics, 145, 160-169.

Gislon, E. (2020), Master Thesis "The sharing economy impact on the hospitality industry: An Airbnb focused systematic literature review", Master's Degree in Engineering and Management, Politecnico di Torino, Italy.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., ... & Cullen, J. (2018). A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies. Nature Energy, 3(6), 515-527.

IEA (2017). Digitalization & Energy. IEA/OECD, Paris https://www.iea.org/publications/freepublications/publication/DigitalizationandEnergy3.pdf

IEA (2017). Energy Technology Perspectives 2017 - Catalysing Energy Technology Transformations. OECD/IEA, Paris.

IEA (2020). Energy Efficiency, IEA/OECD, Paris.

IEA (2020). Tracking Buildings 2020, <https://www.iea.org/reports/tracking-buildings-2020>.

IEA (2021), Appliances and Equipment, IEA, Paris https://www.iea.org/reports/appliances-and-equipment

International Transport Forum (2015). Urban mobility system upgrade: how shared self-driving cars could change city traffic.

Ivanova, D., & Büchs, M. (2020). Household sharing for carbon and energy reductions: the case of EU countries. Energies, 13(8), 1909.

Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., & Creutzig, F. (2020). Quantifying the potential for climate change mitigation of consumption options. Environmental Research Letters, 15(9), 093001

Kikstra, J. S., Vinca, A., Lovat, F., Boza-Kiss, B., van Ruijven, B., Wilson, C., ... & Riahi, K. (2021). Climate mitigation scenarios with persistent COVID-19-related energy demand changes. Nature Energy, 6(12), 1114-1123.

Koomey, J., Schmidt, Z., Hummel, H., & Weyant, J. (2019). Inside the Black Box: Understanding key drivers of global emission scenarios. Environmental Modelling & Software, 111, 268-281.

METI, T. (2015). Top Runner Program–Developing the World's best Energy-Efficient Appliances and More, 96. <www.enecho.meti.go.jp › saving › data › toprunner2015e> (last access August 4, 2020).

Millward-Hopkins, J., Steinberger, J. K., Rao, N. D., & Oswald, Y. (2020). Providing decent living with minimum energy: A global scenario. Global Environmental Change, 65, 102168.

Nakashima, K. (2020), Master thesis "Project of the sharing economy in lodging, Master of Science in Engineering and Management, Massachusetts Institute of Technology, USA.

Ottelin, J., Heinonen, J., & Junnila, S. (2015). New energy efficient housing has reduced carbon footprints in outer but not in inner urban areas. Environmental science & technology, 49(16), 9574-9583.

Packard, V., & McKibben, B. (1963). The waste makers. Harmondsworth: Penguin books.

Poom, A., & Ahas, R. (2016). How does the environmental load of household consumption depend on residential location?. Sustainability, 8(9), 799.

Rao, N. D., Min, J., & Mastrucci, A. (2019). Energy requirements for decent living in India, Brazil and South Africa. Nature Energy, 4(12), 1025-1032.

Rousselot M., Rocha F. (2020), Energy efficiency trends in buildings in the EU, Odyssee-Mure webinar series on Energy Efficiency organized by Leonardo Energy, 8/12/2020.

Sorrell, S., Gatersleben, B., & Druckman, A. (2020). The limits of energy sufficiency: A review of the evidence for rebound effects and negative spillovers from behavioural change. Energy Research & Social Science, 64, 101439.

Statista (2021). Short-term Sharing Is Caring. October 22. https://www.statista.com/chart/26034/revenue-of-short-term-shared-mobility-services-worldwide/ (last access 7/2/2022)

Statista (2022). Estimated number of auto sales lost due to mobile app ridesharing in 2016, by country or region (in 1,000s). https://www.statista.com/statistics/743951/lost-auto-sales-from-ridesharing-apps-by-country-or-region/(last access 7/2/2022)

Ürge-Vorsatz, D., N. Eyre, P. Graham, D. Harvey, E. Hertwich, Y. Jiang, C. Kornevall, M. Majumdar, J. E. McMahon, S. Mirasgedis, S. Murakami and A. Novikova (2012). Chapter 10 - Energy End-Use: Building. In Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 649-760.

Wiedenhofer, D., Smetschka, B., Akenji, L., Jalas, M., & Haberl, H. (2018). Household time use, carbon footprints, and urban form: a review of the potential contributions of everyday living to the 1.5 C climate target. Current opinion in environmental sustainability, 30, 7-17.

Wilson, C., Kerr, L., Sprei, F., Vrain, E., & Wilson, M. (2020). Potential Climate Benefits of Digital Consumer Innovations. Annual Review of Environment and Resources, 45, 113-144.

Wilson, C., Kerr, L., Sprei, F., Vrain, E., & Wilson, M. (2020). Potential Climate Benefits of Digital Consumer Innovations. Annual Review of Environment and Resources, 45, 113-144.

Zhang, Z., and Fu, R.J.C. Fu (2020). "Accommodation Experience in the Sharing Economy: A Comparative Study of Airbnb Online Reviews" Sustainability 12, no. 24: 10500. https://doi.org/10.3390/su122410500

Zissis G., Bertoldi P. (2018). Status of LED-Lighting world market in 2017. Ispra, European Commission, JRC 85636606.

Annual Report

Energy Demand changes Induced by Technological and Social innovations (EDITS)

February 2022

Submitted to

Research Institute of Innovative Technology for the Earth, Japan

IIASA Contract No. 21-122

This document reports the research and coordination activities in the scope of the 'Energy Demand changes Induced by Technological and Social innovations (EDITS) project. The report includes an overview of activities and results of the EDITS scientific teams and future directions emerging from the annual workshop of December 2021.

Acknowledgements: EDITS is an initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA), and funded by Ministry of Economy, Trade, and Industry (METI), Japan.

CONTENTS

PART 1. Energy Demand changes Induced by Technological and Social innovations (EDITS)

ABOUT EDITS....3
SCIENTIFIC BACKDROP....3
CONSORTIUM SETUP AND COORDINATION....4
MEMBERS....6
MEETINGS IN 2021....7
RESEARCH AND MODELING IN 2021....10
RESEARCH AND OUTREACH PLANS FOR 2022 AND BEYOND....17
ANNEX 1: EDITS ANNUAL MEETING....20

PART 2. Progress report 2021-2022: the current state of building sector modeling....28

Note: Links to EDITS documents are included in the text. Most of these have restricted access on the EDITS sharepoint platform, because they are work in progress. It is possible to request access when prompted on the landing page.

PART 1. Energy Demand changes Induced by Technological and Social innovations (EDITS)

The **Energy Demand changes Induced by Technological and Social innovations (EDITS) initiative** started to operate at the end of 2020 after the inaguaral [Virtual Dialogue on Energy Demand changes Induced by Technological and Social Innovations]() was held in December 2020. This report includes an overview of activities and results of the EDITS network in its first year, from December 2020 to February 2022, with an outlook to future directions.

ABOUT EDITS

The **Energy Demand changes Induced by Technological and Social innovations (EDITS) initiative** brings together experts of wide-ranging disciplines to regularly discuss about and engage in the multi-faceted energy demand research. The EDITS community works together based on common interest in interlinked topics, on transferring methodological knowledge, and on exploring modeling innovations across demand-side models.

Levels and structure of energy and resource demands are increasingly recognized as key critical determinants of feasibility, timing, and costs of climate mitigation actions, their SDG synergies, and tradeoffs. EDITS undertakes an examination of demand-driven energy system change, at global and granular levels, with a multidisciplinary viewpoint.

The aim of the experts and researchers forming the EDITS network is to identify gaps and potentials to enhance modeling, analyzing, and communicating the demand-side solutions for climate mitigation and the nexus global systems.

SCIENTIFIC BACKDROP

EDITS is **based on the expansion and deeper understanding Low Energy Demand (LED) scenario**, that was published in 2018 in Nature Energy (Grubler et al. 2018[1]) with ample supplementary information, and updates including the quantifications for water demand (Parkinson et al. 2018[2]). LED entered into a plethora of global scenarios that could meet the Paris Agreement target of limiting global warming to 1.5°C by 2100, but opposed to LED, others relied on negative emissions technologies (IPCC 2018[3]). On the contrary, LED **relies on shrinking the energy system through major lifestyle, behavior, infrastructure, and business model transformations**, resulting not only in a **reduction of global energy use by 40% in 2050** compared to today, but also **gains on equity and the SDGs**.

The higher the demand, the earlier, the more stringent, and the more costly climate mitigation will have to be. Conversely, lower demands increase the temporal flexibility of climate mitigation and reduce the stringency and costs of mitigation actions, thus also reducing the risks of SDG tradeoffs.

EDITS starts off from LED, which is a global scenario. The aim of the joint efforts for LED-type scenario research is to look deeper, with a broader perspective and from a multidisciplinary angle, and explore insights at a more granular level, e.g. in sectors, sub-sectors, and in their intersections, and at subnational levels, too. EDITS develops variations of the LED-narrative and assesses the learning from practical solutions for scenario development and modelling.

[1] Grubler et al. 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy 3 (6): 517-525.
[2] Parkinson et al. 2018. Balancing clean water-climate change mitigation tradeoffs. IIASA Working Paper. IIASA, Laxenburg, Austria: WP-18-005
[3] IPCC 2018. Global Warming of 1.5°C Special Report. URL: https://www.ipcc.ch/sr15/

CONSORTIUM SETUP AND COORDINATION

EDITS is based on the collective interest of a group of researchers and experts, who share research motivation and willingness to assess service demand, energy and material demand, and their modeling. These individuals and teams are all involved in demand research as their regular research agenda, and EDITS provides them an opportunity to enhance their research, discuss with likeminded colleagues, and find new and/or common avenues.

EDITS is managed by the International Institute for Applied Systems Analysis (IIASA), in cooperation with RITE. Key strategies are discussed and approved by a Coordination Team that consists of Keigo Akimoto, Arnulf Grübler, Keywan Riahi, Bas van Ruijven and Benigna Boza-Kiss.

2021 was focused on setting up the structure and coordination, as well as tools for internal communication, external outreach, and explore bilateral exploitation opportunities between the participating teams and EDITS.

The organization of the network has a flexible structure, and it is built on a few cornerstones:

- **Plenary**

All EDITS members are part of the Plenary. They are all invited to regular meetings. IIASA and RITE keeps regular contact with the whole community.

- **Regular meetings**

Intellectual and inspirational exchanges are organized in Quarterly Meetings and an Annual Workshop. In 2021, three Quarterly meetings were organized and one Annual Workshop.

These meetings are addressed at the whole EDITS Network. The Quarterlies are working meetings, focused on reporting and common discussion on the work being undertaken by

The section “Meetings in 2021” reports on how and why these meetings were organized.

- **Working Groups**

EDITS is organized into seven working groups currently. This reflects the starting point of the EDITS research, and it is open for change. This setup is regularly discussed, and the structure is flexible and also expected to adapt to changes in the research goals and focus. At the moment, the demand research in EDITS is focused on reviews of the current practices and gaps, which are explored in sectoral groups (Working Group 1-Buildings, Working Group 1-Transport, Working Group 1-Industry), developing the fine-tuning and granular reflection of LED (Working Group 3-Narratives), and testing LED scenarios (Working Group 3- Protocol) and data needs and data availability (Working Group 2-Data). The third sub-group of Working Group 2 (Synthesis) is bridging current research activity to progress in the next years in EDITS.

Each Working Group is lead by two people, the Co-leads. Anybody from the EDITS membership may join any Working Group. Working Groups have dedicated activities and communications, e.g. specific email alias, as shown in Table 1.

More information on the actual activities of the Working Groups in 2021 is found in section “Research and Modeling in 2021”.

Table 1. EDITS Working Groups in 2021 and 2022.

Working Group	Topic	Co-lead		Group email address
Coordination	Oversight of project	Keigo Akimoto	Keywan Riahi	edits@iiasa.ac.at
WG 1-Buildings	Buildings sectoral modelling	Alessio Mastrucci	Leila Niamir	edits-buildings@iiasa.ac.at
WG 1-Transport	Transport sectoral modelling	Paul Kishimoto	Luis Martinez	edits-transport@iiasa.ac.at
WG 1-Industry	Industry/materials modelling	Stefan Pauliuk	Dominik Wiedenhofer	edits-industry@iiasa.ac.at
WG 2-Data	Data and models	Oreane Edelenbosch	Nan Zhou	edits-data@iiasa.ac.at
WG 3-Narratives	Empirical grounding, LED-driven narrative	Charlie Wilson	Arnulf Grubler	edits-narratives@iiasa.ac.at
WG 3-Complementarity Protocol	Complementarity protocol development	Masahiro Sugiyama	Bas van Ruijven	edits-protocol@iiasa.ac.at
WG 3-Synthesis	Synthesis	Shonali Pachauri	Massimo Tavoni	edits-synthesis@iiasa.ac.at

- **Working Group meetings**

Working Groups meet outside and inside the regular meetings, to progress on agreed common research activities. Members of the Working Groups also work together on shared documents continuously. The meetings offer platform for actual collaborations, concrete research, writing and modeling activity to be discussed.

- **Communication and document organization**

For easier and data-respecting communication, IIASA installed dedicated email aliases in March 2021. For the plenary the address edits@iiasa.ac.at, is used, and the Working Groups have respective email addresses (see in Table 1).

IIASA also operates a shared collaboration and communication platform under Teams and Sharepoint. These are accessible at: EDITS Teams and Documents.

All of the communication and documents are accessible only for the EDITS Network.

- **Website, logos, templates**

To support the EDITS initiative, IIASA has set up an EDITS website, and developed logos and templates in cooperation with RITE and with the review and comments of the EDITS community.

  - EDITS website
  - Templates for presentations and documents available in the respective Sharepoint folder
  - Logos, all of which are saved and available for all members in the respective Sharepoint folder (see Figure 1).

A tailored style was developed and used in all materials.

In case of the logo, the whole network is represented by a general logo (with an imaginary planet in the colors of energy efficiency), while Working Groups also have respectively tailored logos with respective icons in the same style.

Working Group 1-Buildings

EDITS network

Working Group 1-Transport

Working Group 2-Data

Working Group 1-Industry

Working Group 3 (for all subgroups)

Figure 1. EDITS and Working Group logos.

MEMBERS

As of February 2022, the EDITS network has 127 individuals (Figure 2) representing 62 Research Teams. EDITS membership is by invitation only.

When a person or team would like to join or would like to suggest new member(s), they are requested to send an email to IIASA, and will be contacted for membership details, mainly to understand their interest in different Working Groups. Joining organizations are expected to submit a one-page information sheet to describe their energy demand related research agenda and how it relates to the work in EDITS (template at request).

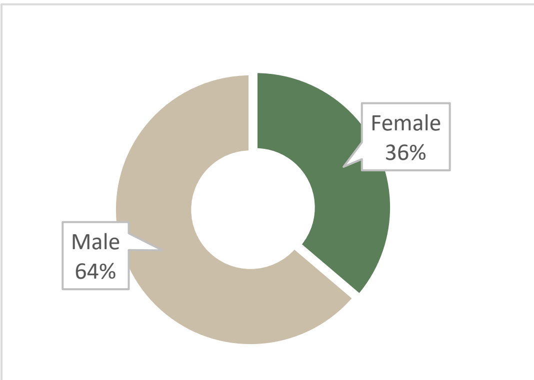


Figure 2. Gender distribution of EDITS members (individuals) as of February 2022.

EDITS members are offered to choose Working Group membership. 63% of all members take part in at least one Working Group, which indicates a higher level commitment than being "only" a plenary member (but not always). Figure 3 illustrates the membership status of each Working Group.

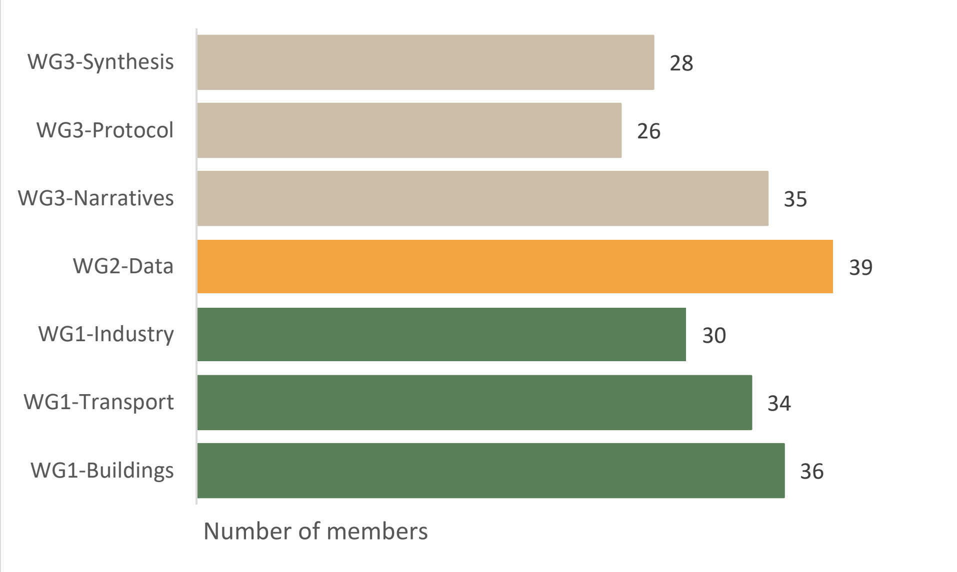


Figure 3. Working Group sizes according to membership as of February 2022.

MEETINGS IN 2021

The intellectual, motivational discussions, and thought exchanges are based largely on the regular meetings in the forms of Quarterlies and an Annual Workshop. These meetings provide the backbone for EDITS collective knowledge, sharing information and ensuring progress in all Working Groups.

Regular meetings

In 2021, four regular meetings were organized, of which 3 Quarterlies (March-April; June; September), and an Annual Workshop (Table 2).

Table 2. Regular meetings in 2021.

Meeting name	Session	Date	Participants
EDITS 1st Quarterly	Session 1	30/03/2021	59
	Session 2	*	*
	Session 3	16/04/2021	62
EDITS 2nd Quarterly	Session 1	15/06/2021	58
	Session 2	22/06/2021	61
	Session 3	29/06/2021	53
EDITS 3rd Quarterly	Session 1	27/09/2021	57
	Session 2	28/09/2021	56
Annual Workshop	Session 1-2	09/12/2021	69
	Session 3-4	10/12/2021	66

* Note: Session 2 hosted the kick-off meetings of Working Groups. Therefore these were distributed meetings at individual times. The list of these can be found in Table 3

Quarterlies

The size and focus of the Quarterlies were varied throughout the year, in order to test what works well, and what needs to be changed.

The **first Quarterly** was held as three Sessions between 30 March and 16 April. The first and the third Sessions hosted plenary discussions and the establishment of the Working Groups. The second Session was a distributed/decentralized session, where each Working Group organized their first Working Group meetings. These have become the kick-starters of working group meetings during the following months. They changed into on-demand meetings after the first Quarterly, with a meeting regularity adapted to the actual work done in the Working Group. These are reported below under section "Working Group meetings". Therefore, subsequent Quarterlies were focused primarily on reporting back on the work during the intermittent periods, providing a platform for Working Groups interaction, and to discuss one or two intellectually challenging topics.

The **second Quarterly** had three sessions on subsequent Tuesdays on three weeks of 15 June, 22 June, 29 June. Each session gave an opportunity for each Working Group to present (1) their overall research aims, (2) their 2021 specific goals, (3) methods, (4) expected outputs, (5) interaction plans with other Working Groups.

The **third Quarterly** was planned to be more compact, by then removing the Working Group daily activities outside of the Quarterly meetings. Thus, it was organized on two subsequent days.

After testing these setups, a general sentiment was that compact meetings on subsequent, or relatively close dates are most effective, and that the Quarterlies should focus on one-two discussions relevant for the whole network, and on reporting back from the Working Groups, which should also encourage Working Group interactions.

Annual Workshop

The EDITS Annual 2021 meeting was the second annual meeting of the Energy Demand changes Induced by Technological and Social innovations (EDITS) network, a finale of an intensive year of collaboration.

The EDITS Annual 2021 meeting was preceded by a series of three joint IIASA-RITE international workshops aimed at exploring the potential for reducing energy demand to mitigate greenhouse gas emissions in the context of sustainable development. The inaugural meeting was held in Nara, Japan, 25-27 September 2018, the second scoping meeting was held in Laxenburg, Austria, 11-13 November 2019. The Virtual Expert Dialogue of 2020 was held online on 8-11 December 2020, and served as the first Annual Meeting to kick-off the demand-side research and model intercomparison project, EDITS.

After a year of intensive work and regular meetings, the community was invited to meet online with two key goals:

- To discuss selected fundamental topics that underlie the energy demand / service demand research and policy making.
- To evaluate the activities of 2021, take stock of achievements and progress so far, and plan for 2022.

The meeting was organized in a way to encourage participants to participate. Acknowledging that not everyone prefers to speak up during larger plenary sessions, we added features, where other types of interactions were possible. These included:

- Two types of break-out groups
- MIRO platform for comments and ideas
- Gather.town meeting for more relaxed conversations
- Zoom chat as usual
- Encouraged to send in more comments by email before or after the meeting, which some organizations did, especially if they could not attend the EDITS Annual 2021 Meeting

According to the participant recording function of zoom, the meeting had altogether 96 participants on day 1 (sessions 1 and 2) and 81 participants on day 2 (sessions 3 and 4). Typically 50-55 people were present at given sessions at the same time.

The meeting also featured two socializing opportunities, to resemble a personal meeting. The first social coffee break was organized at the end of Day 1, and participants were invited to join the platform Gather.town. This is an online meeting tool, where participants have avatars of their choice, and they can walk around in a place freely and meet others in predefined corners, where they can participate in private discussions or even games. The set-up was created beforehand by IIASA as a country house with cozy corners and smaller and larger tables to sit around. Participation rated at around 30 people and the coffee break was one hour long.

The EDITS Annual 2021 meeting was organized in four sessions:

- Session 1 included motivational speeches, including a report from EDITS participation at the COP26, and real-life examples of low-energy-demand policy-making and commercial innovations to transport service provision.
- Session 2 invited the Working Groups to give a brief overview of their activities and achievement during 2021, which was followed by a deeper assessment and discussion of real-life examples of built environment solutions that respect or represent LED futures.
- Session 3 discussed ways to balance sufficiency and innovation perspectives in the light of low energy demand scenarios.
- Session 4 consulted all members of the community to express their views on the future directions and the specific plans for 2022 in the scope of EDITS.

We encouraged all participants to take active part in the meeting using the alternative opportunities provided and described above.

Working Group meetings

Working Group meetings are organized based on the working needs of the WGs. Certain Working Groups rely a lot on meeting and thought exchange, such as WG1-Buildings and WG1-Industry, while others work more in writing and small groups, e.g. WG3-Narratives, or a combination e.g. WG3-Protocol.

Table 3. List of Working Group meetings in 2021-early 2022.

meeting	date	participants
Working Group Narratives	31/03/2021	27
Working Group Buildings	09/04/2021	16
Working Group Transport	04/09/2021	15
Working Group Data	12/04/2021	27
Working Group Industry	14/04/2021	25
Working Group Protocol	15/04/2021	69
Working Group Buildings	17/05/2021	17
Working Group Data	21/05/2021	16
Working Group Industry	23/06/2021	24
Working Group Data	09/09/2021	7
Working Group Buildings	20/10/2021	20
Working Group Protocol	20/10/2021	3
Working Group Industry	21/10/2021	22
Working Group Protocol	25/11/2021	3
Working Group Protocol	26/11/2021	8
Working Group Industry	09/12/2021	27
Working Group Buildings	18/01/2022	21
Working Group Transport	19/01/2022	17

RESEARCH AND MODELING IN 2021

Energy and resource demands themselves are intermediary variables, and it is the services and amenities that the use of energy and other resources provide. The efficiency of resource use and the efficiency of alternative service provision models thus move into center stage of climate mitigation from a demand, or end-use perspective. Because of the high heterogeneity of consumers and the multitude of demand types (food, shelter, mobility, communication, etc.) the theoretical understanding and modeling of "demand" (outside aggregated simplistic formulation) remains limited and fragmented, as are resulting capabilities to propose and to assess demand-side policy interventions from the twin angle of climate mitigation as well as of promoting the SDGs.

The overall EDITS goals are to identify gaps and potentials to enhance modeling, analyzing, and communicating the demand-side solutions for climate mitigation and the SDGs. This is a long process, and includes critical research steps.

The specific goals for EDITS on a longer term were defined based on the summary of take-aways at the Virtual Meeting in December 2020 (see EDITS project report 2020). Accordingly, specific goals can be distinguished for a) demand analysis, b) demand modeling, c) communication.

EDITS had the following research goals in 2021:

- Mapping the current state of demand research in various aspects
- Identify data needs, data gaps, data availability
- Describe current modeling practices for demand to understand what works well, and what needs to be improved
- Develop and test a small scale model comparison, that can be used as the basis for a model complementarity protocol
- Re-interpret the original LED scenario

Research organization and tools

- **Research support tools**

EDITS hosts high level scientific activity, which result in different outputs that IIASA and the community will collect and track.

Input and output data and datasources will be collected in a shared metadata repository, developed by Working Group Data. This is currently established as a central repository iiasa/edits-data on GitHub. Suggested platform to be used in the long-run is Zenodo[4].

The EDITS Community is in the process of preparing XX **scientific papers**. A central repository for these is created in the online tool Zotero.

EDITS members are expected to acknowledge the network as a source of funding and/or inspiration, in their outputs. The suggested text to be used is: *{Name or Institute} received funding from the Energy Demand changes Induced by Technological and Social innovations (EDITS) project, which is part of the initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA) (and funded by Ministry of Economy, Trade, and Industry (METI), Japan).*

- **Model lists**

A registry of models owned by the teams that are members in EDITS, and other relevant demand models that we have communicated during the year has been done. These models have been invited to be part of the model complementarity exercises. The list of models is in Table 4, and further information can be found in the Sharepoint.

By February 2022, EDITS have collectively collected **29 key demand models around the world**. We started from a collection of models hosted by the EDITS Members, but expanded the data collection to models whose owners have not joined or are less active in EDITS, but were willing to answer a few survey questions or interviews.

Table 4. List of demand models in the sight of EDITS.

SAFARI	MESSAGE-Access-End-Uses	MESSAGE-buildings
Rumi (PIER)	TREES	MESSAGEix-transport
Urban Building Energy Model for Japanese Commercial Building Stock	UK National Household Model	Tsinghua-life cycle analysis model (TLCAM)
ITF Outlook 2021	MoMo	MISO-model v2
MESSAGEix-Materials	3CSEP-HEB	Amadeus-ORPHEE
FORECAST	RECC	COFFEE
BENCH	EDGE-Buildings 2.0	DNE21+
US-REGEN	BLUES (Brazilian Land Use and Energy System)	MAT-dp
TIMES Austria	PoTENTIA	IMAGE-Transport
BISE	Vehicle-Stock-Model	

[4] https://zenodo.org/, Key benefits: run by CERN's Data Centre; promotes Open Science; uploads are assigned a DOI); available version control; GitHub integration.

The host organizations of the models identified in EDITS are scattered around the globe (Figure 4).

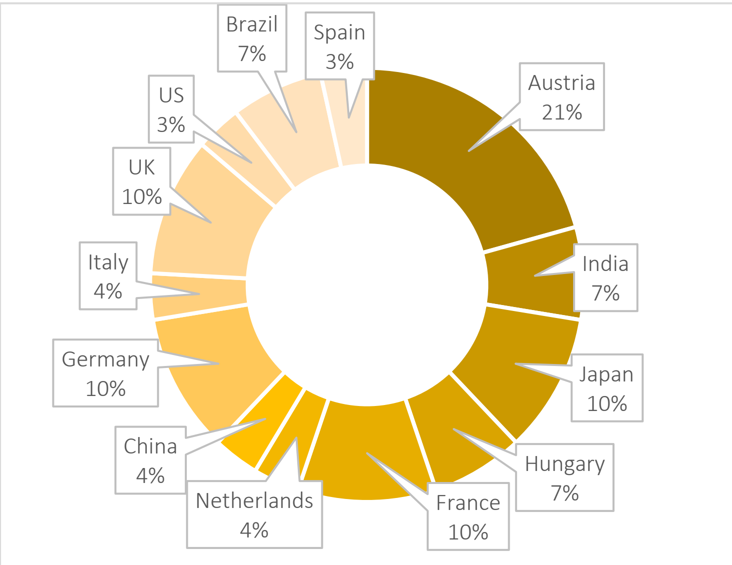


Figure 4. Host countries of the identified models within EDITS in 2021.

14 models of the identified 29, have a global coverage or focus, others are national or city level. This will allow for a complementary modelling of different geographical levels.

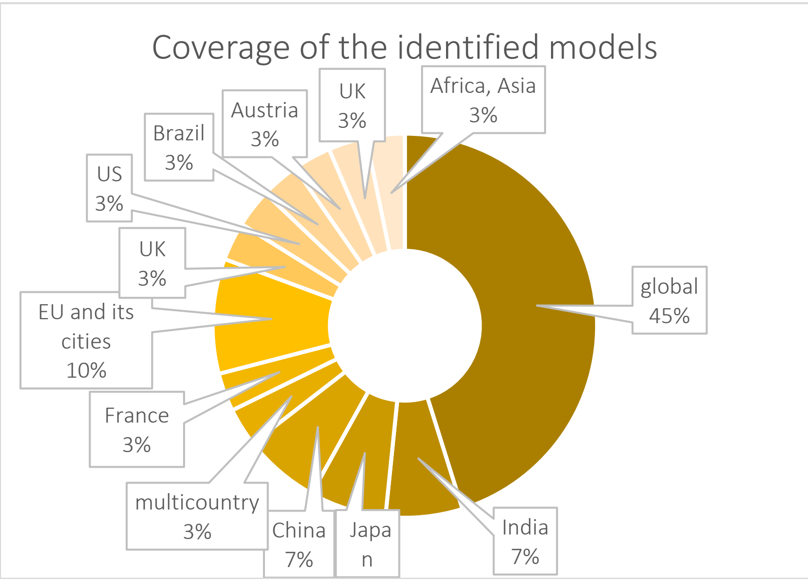


Figure 5. Coverage of the identified models within EDITS in 2021.

Working groups

The actual research and modeling work, i.e. daily activities are organized in Working Groups. The seven Working Groups were already presented above in the Section "Consortium setup and coordination". Here, a report on their 2021 activity is presented.

Table 5. Overview of Working Group activities and outputs during 2021.

WG	Key Output	Status as of February 2022	WG meetings	Expected input from other WGs	Interaction with other WGs
WG1-Buildings	Review paper: model mapping	Paper Precis in ARER accepted, draft paper available, to be final by June 2022	Per demand, ca. bimonthly + sub-groups for work	WG-N: sector specific scenario narratives	Collaborate with WG-Data regarding the survey info collection
WG1-Transport	Two papers in preparation: Methods/theory paper and harmonized model documentation	Transport efforts used for testing data documentation (for WG-Data), and first paper draft available	During the Quarterlies and in combination with WG-Data	WG-N: sector specific scenario narratives WG-Data: on types of transport data	Collaborate and test WG-Data methods
WG1-Industry	Review paper on modelling approaches	Paper Precis to ARER submitted, awaiting response, and draft paper available, to be ready mid-2022	Linked to Quarterlies, but as separate sessions + on-demand to progress	WG-N: sector specific scenario narratives	Collaborate with WG-Data
WG2-Data	1. Metadata collection, 2. Review paper on data needs and data framework	1. Data solicitation protocol and its testing done, 2. Draft outline and content, to be ready end of 2022	Per demand, cross-WG meetings	WG1-all: testing WG3-Protocol: Model output data consolidation	Collaborate with WG1-all on the data collection and testing Interact with WG-Protocol on data needs, gaps and template formats
WG3-Narratives	Implementation guide for sectoral WGs & enriched LED narratives	Drafts on specific narrative themes	Per demand, small group meetings	WG1-all: Opportunities and challenges of LED implementation	Meetings with WG-Protocol to feed narratives into LED-modeling exercise
WG3-Protocol	MCE protocol(s) test design and test run with volunteering models	Conceptual framework established, testing done.	Linked to Quarterlies, but as separate sessions + on-demand and meetings with WG1 sub-groups	WG2-Data: data-interlinkages WG3-Narratives: common narrative elements to be used on the complementarity modeling	WG1-all: definition of sector specific narrative elements WG2-Data
WG3-Synthesis	Synthesis of the work in WG1 and WG3	To be defined later	Coordination meetings, WG meetings later	Feed from all WGs to synthesis findings	Regular communication with other WGs

Working Group 1 includes sub-groups according to sectors (buildings, transport and industry).

- These groups review existing sector models, compare or find complementarity opportunities across models.

- They support each other in development or find ways to share knowledge and learning opportunities.
- Expected outcome in 2021-2022: Research review papers on the how sectoral demand models to reflect Low Energy Demand scenarios.

Below is a summary of 1) aims of the sub-groups defined by the members, 2) research and results in 2021, 3) meetings and collaboration in 2021.

Working Group 1-Buildings

1) Aims of the subgroup in 2021
- Identify gaps and expand knowledge in building sector modelling towards representing social and technological transformation.
- Identify, prioritize and establish collaborations within and beyond the Working Group.

2) Research and results in 2021
- Literature review;
- Identified building demand models summing up a list of 27 demand models, and established contacts and collected information from them.
- A second phase of the model survey was collected, to collate information about building demand modeling practices
- Prepared and submitted a paper précis to Annual Review of Environment and Resources (ARER) on "Modeling socio-behavioral, technological and infrastructural innovations for reducing energy demand in buildings" (mapping paper);
- Prepared "Guideline document" by co-leads to facilitate the writing ARER paper procedure and increase collaboration in the author team;
- Established a dedicated Zotero literature bank.
- Collaborative writing of the paper "Modeling social, behavioral, technological, and infrastructural innovations for reducing energy demand in buildings".

3) Working Group interlinkages in 2021
- Contributed to the activities in WP2-Data and WP3-Protocol and Narratives and provided data inputs and outputs from relevant models in the EDITS community;
- g. Contribute to activities of WG1-Industry and WG1-Transport, particularly on designing review papers.

4) Activities and meetings in 2021

a. Regular series of ca. bi-monthly working group meetings;

b. Active participation at the Quarterlies and the Annual Workshop.

Working Group 1-Transport

1) Aims of the subgroup in 2021
- Identify gaps and expand knowledge in transport sector modelling towards representing social and technological transformation.
- Identify, prioritize and establish collaborations within and beyond the Working Group.

2) Research and results in 2021
- Literature review;
- A transport modeling review paper was started: conceptual development and draft outline; Paper draft is being developed.

3) Working Group interlinkages in 2021
- Collaboration with the other WG1 groups to develop consistent modeling approaches and narratives.
- Strong collaboration with WG2-Data, with regular shared meetings and serving as a test data collection team.

4) Activities and meetings in 2021
- First shared meetings with WG2-Data;
- Separate meetings in the second half of 2021, in order to focus on the review paper.

Working Group 1-Industry

1) Aims of the subgroup in 2021
- A review and research roadmap for modelling the sustainability transformation of the industrial sectors in response to deep demand-side transformations

2) Research and results in 2021
- Literature review of industry and material demand modeling in the scope of LED scenarios;
- Preparations for a review paper: Low energy & materials demand net-zero GHG futures for industry – a critical review of modelling approaches and their capabilities to deliver transformative insights to be submitted to ARER.
- A paper précis to apply for ARER publication.

3) Working Group interlinkages in 2021
- Close exchanges with WG buildings, WG mobility, WG meta database and WG

4) Activities and meetings in 2021
- Working meetings linked to Quarterlies (organized for the same or close dates)
- On-demand follow-up meetings

Working Group 2: Data and models

1) Aims of the subgroup in 2021
- .

2) Research and results in 2021
- Literature review of similar data collection examples;
- Metadata repository that reports on data availability and description: collection instructions, including Full description of motivation and Worksheet (final pages).
- Central repo/proof-of-concept code: iiasa/edits-data on GitHub
- Review paper on data needs was started and the concept and framework set-up.

3) Working Group interlinkages in 2021
- Close collaboration with WG1-Transport, testing of data-work.

4) Activities and meetings in 2021
- First shared meetings with WG1-Transport;
- Separate meetings in the second half of 2021, in order to focus on the review paper.

Working Group 3: Scenarios/narrative and model complementarity

The Working Group has three sub-groups that together aim at improving both the narrative and the modeling of energy demand consistently and with an enriched detail.

Working Subgroup 3-Narratives

1) Aims of the subgroup in 2021
- To enrich the original LED scenario narrative by asking: (1) how might a LED future happen? (2) what would a LED future be like?
- The first question should strengthen the achievability of a LED future by thinking through the drivers and dynamics of change, including policy, innovation, digitalisation, new service opportunities, while recognising uncertainties and the plurality of possible outcomes.
- The second question should strengthen the desirability and understanding a LED future by thinking through what it would mean for wellbeing, work, material flows, time use, equity and decent living, while recognising heterogeneity and regional variation.

2) Research and results in 2021
- A quantitative framework 'DETRAS' decomposing two-region sectoral final energy 2020-2050 in LED into Activity, Structure, and Intensity components
- Analyses of cross-cutting topics to build up the consistent scenario narrative.

3) Working Group interlinkages in 2021
- LED implementation through interaction with WG3 Modelling Protocol and sectoral WGs as required.

4) Activities and meetings in 2021
- Working meetings with sub-teams, who have produced analyses in the topics: 1) digitalization and dematerialization, 2) decent living standards, 3) innovation.

Working Subgroup 3-Complementarity Protocol

1) Aims of the subgroup in 2021
- The overall aim of the sub-WG was to prepare the development of a scenario protocol for a model complementarity exercise (MCE) and to implement the EDITS scenario narrative consistently into heterogenous and diverse modeling frameworks. The protocol will specify how different types of models should be run in order to get insights into low-demand scenarios and policy synthesis.
- The protocol for the EDITS model complementary exercise will help gain insights into the LEMD scenarios.

2) Research and results in 2021
- Test run of the MCE = Demonstrate the proof of concept for MCE
- Preparations for the initiation of a full MCE
- Methodological discussions among the Co-leads, the WG members and with other WGs

3) Working Group interlinkages in 2021
- MCE protocol and related outputs will feed in to all other WGs/the entire group, particularly synthesis WG.

4) Activities and meetings in 2021
- Working Group meetings at the Quarterlies.
- Bilateral strategy meetings with the Co-leads.
- Always participated at sectoral sub-WG meetings, where the test MCE was presented and volunteers found.

- Collaboration with WG2-Data.

Working Subgroup 3-Synthesis

1) Aims of the subgroup in 2021
- The sub-group is responsible for synthesis across scenario implementations at different sectors and levels.
- The sub-group is different from the other in that 2021 was not meant to be an active year. On the other hand, longer term aims were underlying the members participation in other WGs. The overall aim of the WG is to synthesize the work carried out in the other WGs and summarize the main insights of the project, specifically in terms of (i) defining boundary conditions (e.g. demographics, economic convergence) which are input to the models and their coherence with the LED narratives, and (ii) evaluating the output of LED scenarios through developing and applying a multi-dimensional framework.

2) Research and results in 2021
- Presentations at meetings, participation in other WGs (Building, Industry, Data, Narratives);

3) Working Group interlinkages in 2021
- Summary articles on EDITS scenarios and analyses of the EDITS database will feed into this WG, thus WG-Synthesis members took part in other WG activities in 2021.

4) Activities and meetings in 2021
- Regular bilateral meetings between the co-leads in order to assess results in other WGs.

RESEARCH AND OUTREACH PLANS FOR 2022 AND BEYOND

IIASA continuously exchanges research information and plans EDITS research targets to be interlinked and additional to the internal research goals the participating researchers and experts

Research ideas for the year 2022 and beyond were discussed at the Annual workshop.

1) EDITS and you: what have you/your team gained from EDITS and what are you looking forward to for next year?
    - EDITS as a hub for demand-research, where participating teams have interest and working agendas:
        - Connect communities in a 'safe space'
        - The topics discussed are valuable and varied
        - Big to small questions are all picked-up: from megatrends to details
        - Combine different modeling paradigms
    - Learning from others
        - Learning about pathways to an LED future without a lot of clear analogues to draw from, which is important from a policy perspective.
        - Learning from other disciplines (e.g. buildings – transport)
        - Connections among different geographical knowledge
        - It is possible to present one's research and get feedback, valuable context
        - There is trust and collegiality among members, which is very unique
    - Connecting disciplines is valuable and should be further strengthened
        - There are representatives of different disciplines already, however sociologists and psychologist could be further invited
        - Exciting to hear how the demand narratives link to policy needs and can influence policy

- Networking value:
    - EDITS opened a lot of opportunities to reconnect with an exciting network of people.
- EDITS was quoted by many as a favorite project, which fills the gap of demand side perspectives
    - Making an impact will be a measure of our success.
- Suggestions for additional topics:
    - Impact of whole energy systems of demand reduction
    - Food and digitalization
    - Understanding impacts of digitalization on behavior and demand
    - 3D impact of LED products in different sectors
    - Implicit costs of deploying energy efficiency techs or sufficient energy consumption – identify why gaps exist through estimating implicit costs and barriers
    - Better understanding of the whole project – improve the project – also explain the benefits of the project to funders
    - More on feasibility of LED across different countries and constraints
    - Understanding consumer behavior
    - Issue of demographic change – shrinking population in some parts of the world (Korea) and ageing, - understanding the implications of this for demand, etc.

2) Heterogeneity in EDITS work: how to move towards improved representation of Global South in membership and in the work?
    - EDITS offers opportunity to strengthen N-S collaboration
        - This would need more attention: How to 'crash the wall' between global north and global south (AR6 has 10 regions, but that is still not enough)
        - New initiatives would be interesting within EDITS to explore needs of the global south, as well as to strengthen capacity building
    - Models and research should increase representation of global south, also in reflection of data gaps
        - Data for Global South a big issue still: data gathering efforts could be integrated into EDITS
        - There is variation within the Global South, too, which should be captured

3) Should we change the regularity and/or types of meetings?
    - Regular meetings appreciated:
        - Remaining connected during the pandemic – regular connections and meeting were appreciated
    - Online for most meetings work, but at least one in-person meeting would be appreciated

4) Policy makers show interest in Demand Scenarios, what is your interest in the EDITS network's balance between research and policy impact?
    - Connect with policy-makers in the long-run at least, is desirable:
        - For example, write opinion pieces that are easily communicable
        - Suggestion to make the most of EDITS unique brain-power and explain the need for rebalancing policy and funding priorities to demand side and wellbeing
        - EDITS could team-up with intermediaries to policy: e.g. European Climate Foundation, and similar in other countries
        - Window of opportunity to influence demand side policy making now is high and should really try to harness the efforts of EDITS for this.

    - Avoid the EDITS-silo effect and EDITS should go beyond self- referencing
- Find the right message for policy-makers:
    - Emphasize the benefits (eg employment) of infrastructural and efficiency strategies to appeal decision makers
    - Focus on demand side and wellbeing connections
- Style and format:
    - The community could write policy-briefs to be ready for policymakers, or op-ed.
- Beyond policy-makers:
    - Do not ignore connecting with the general public
    - EDITS might explore how the acceptance of LEMD / LEMD solutions can be accepted, how business can be connected
    - EDITS could also connect to justice-sufficiency communities
    - Connect with external industry actors, policy makers and consumer groups would be welcome – bidirectional learning and generating dialogue is something that can help EDITS' learning and to make impact too

ANNEX 1: EDITS ANNUAL MEETING

EDITS builds on the increase in acknowledgement for enhanced demand-side research and modeling. The project strives for a deeper understanding of demand-driven energy system change, at global and granular levels. The EDITS community pursues collaborative activity to identify gaps and potentials to enhance modeling, analyzing, and communicating the demand-side solutions for a transition towards sustainable energy systems, rapid climate mitigation and the achievement of the SDGs.

Levels of activity and structure of energy and resource demands are increasingly recognized as key critical determinants of feasibility, timing, and costs of climate mitigation actions and their SDG synergies and tradeoffs. Energy and resource demands themselves are intermediary variables, and it is the services and amenities that the use of energy and other resources provides.

Organization

In spite of the hopes and previous discussions for an in-person meeting, the EDITS Annual 2021 Meeting was held again in turbid and uncertain times, with the looming COVID-19 pandemic affecting life and travel plans. Therefore, it was decided to organize it again fully online.

The meeting took place on the online platform zoom, which has been used overall during the whole year.

The dates and times were selected after consultations with the whole community, with particular attention to Working Group members and organizations with specific tasks in the scope of EDITS. Timing the meetings is usually a challenge because EDITS has participants from around the world, thus located in many different timezones. The EDITS Annual 2021 Meeting was compact and targeted, to be able to respect participation from as many timezones as possible.

Day 1: 9 December 11:00-15:30 [CET] | 10:00-14:30 [UTC] | 19:00-23:30 [JST] | 5:00-9:30 [EST]

Day 2: 10 December 11:00-14:45 [CET] | 10:00-13:45 [UTC] | 19:00-22:45 [JST] | 5:00-8:45 [EST]

Recordings are available through the zoom platform:

- For Day 1 with access passcode: &2R0vnS$
- For Day 2 with access passcode: wa5&YMbd

The recordings are also found in the EDITS sharepoint site, for which access may be requested from IIASA (by sending an email to Pat Wagner at wagner@iiasa.ac.at).

Session 1. Motivation and framing

The EDITS Annual 2021 was opened by **Keigo Akimoto (RITE)**, who reflected on how energy-demand research and policy support has been gaining attention. The Japanese government has set out ambitious emission reduction targets of 46% emission reduction by 2030, and reaching climate neutrality by 2050. There is a need for new scenarios and showing how to deliver these targets. In this framework, the government is particularly interested to base strategies on drastic energy demand reduction, while respecting continuous service levels.

Keywan Riahi (IIASA) added that EDITS is and will be in the spotlight, because targets and ambitions are lining up, respecting energy efficiency as the first fuel, and reducing demand to also alleviate the pressure on supply and other technologies are imperative. He mentioned the example of real-life solutions that are gaining attention, and that more of them are needed, and EDITS has a role to connect both with policy and with the industry. The Klimaticket for public transport was just introduced in Austria, which is an annual pass for about 1000 EUR that allows unlimited use of all public transportation.

Joyashree Roy (Asian Institute of Technology) talked about the importance of connecting science and policy. She lead the discussion panel of EDITS at the COP26 side-event, organized under the Japanese Pavilion.

John Barrett (Center for Research into Energy Demand Solutions, CREDS), as a new member of EDITS, presented a seminal low energy demand modeling and research work carried out at the national level for the UK.

The UK model is based on the ideas of the LED scenario, and explores the key energy demand service sectors, and works with the representation of the interlinkages (see Fig. 1).

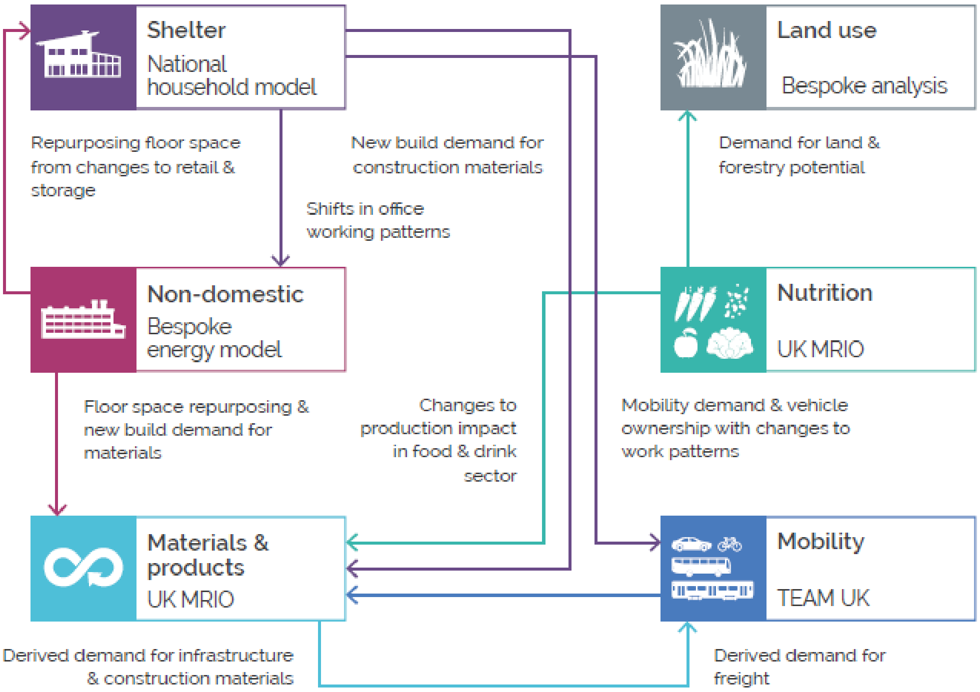


Figure 6. CREDS UK energy demand model structure respecting the interlinkages among the sectors.

They developed four possible scenarios in terms of demand reduction. We could ignore, steer, significantly shift or completely transform our energy demand. The most ambitious, the TRANSFORM scenario is projected to lead to 52% of energy demand reduction in 2050 compared to 2010, which is composed of a 62% reduction in agriculture, 26% reduction in industry, 48% in non-domestic sector, 52% reduction in the residential sector, and 68% reduction in transport energy demand.

The team has been contacted by the UK government, who are very interested in developing ambitious energy demand scenarios and to translate these into policy objectives and measures.

Sampo Hietanen (WHIM / MaaS Global) was the invited expert of the Session. He is the CEO of the world-famous mobility as a service (MaaS) company, WHIM, which started originally in Helsinki, where it has gained major popularity. They offer a combination of public transport, shared cars and non-motorized solutions in different packages. This has allowed users to get rid of their car ownership, and use the WHIM mobility on demand. Since its start other cities have also incorporated WHIM as an offer in their mobility solutions, such as Vienna, Belgian cities, Tokyo.

He explained that business and environment need to go hand in hand, and policies have a role to ensure that the social benefits are reaped. From a business perspective, he explained that there is a large interest in alternative solutions for mobility, because people do not want to own a car necessarily, they do not mind the technology that they use (in general), but they need to do their errands and interests, for which they often need to get from A to B. Therefore, a business needs to provide solutions for that. He explained that WHIM "plans the dreams of people into their services".

Finally, he discussed how his views on the users have changed. The general impression is that young, single people are the main targets of MaaS, however, he found that middle-aged populations were also happy to abandon their cars and use the flexible mobility services. This allows them to forget about maintenance, garage space and so on.

Session 2. Scientific progress in EDITS and bringing lessons from real-world innovations to EDITS

After a brief review of the WG 2021 progress[5], an interactive session about "learning from real-life innovations for urban LED scenarios" was organized by **Souran Chatterjee** (Central European University, Hungary).

The LED scenarios is about practices that currently seem to be extreme or implausible on a larger scale becoming wide-spread. A short presentation kick-started discussions in break-outs to explore a range of niche solutions and innovations at the social, infrastructural, technological and organizational levels in the wider buildings sector, i.e. urban and built environment (see Fig. 2.). Changes in the building stock and energy demand in buildings are slow. While transformational shifts in the sector could offer major energy demand reductions and climate mitigation opportunities, cultural, technological and political factors limit its responsiveness. Thus, in spite of the wide-ranging public policies and huge steps in technology innovation, the energy demand reduction potential is hardly tapped. Their potential impact and how their roll-out could be analyzed and/or modelled in the scope of EDITS were the main questions.

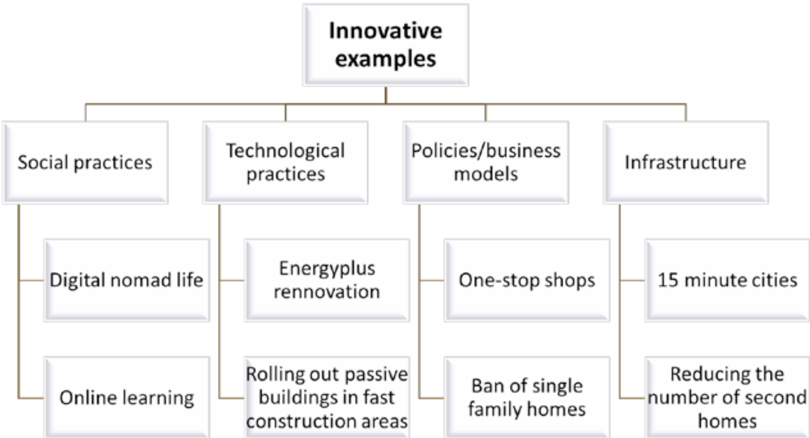


Figure 7. The examples of real-life LED solutions discussed in Session 2.

The following topics were discussed in the break-out groups:

- What methods/activities would help to bring industrial knowledge to the scientific community?
- How (if at all) should LED scenarios capture possible adverse well-being impacts of real-life LED cases?
- What are the challenges of extending or rolling-out currently niche examples for national, regional or even global LED models?
- How to model the rebound effects of LED examples?
- Sector coupling: Is it possible? By when (market and system readiness)?

Session 3. Perspectives on energy demand transformations

The original Low Energy Demand scenario (Grübler et al. 2018) focused on energy-demand innovation in the technological, social, business and infrastructure domains, akin an "efficiency strategy" with significant upstream implications and assuring improved services at decent living standards for all (Rao and Min 2017). Others have argued that low energy demand should be achieved through sufficiency, putting a maximum level on consumption either in service or resulting energy terms (Millward-Hopkins, 2020; Steinberger & Roberts 2010). While there are sufficiency aspects included the LED scenario narrative, such as converging living space sizes and achieving minimum decent standards of

[5] A summary of the Working Groups' reports and progress will be provided as part of the Annual Report of EDITS.

living thresholds, the scenario does not take sufficiency as main entry point for achieving low energy demand.

In many of the discussions of the EDITS network, the differences, commonalities and complementarities between the sufficiency and energy demand innovation approaches have been alluded to, but these aspects were not discussed explicitly previously.

The session was moderated by **Arnulf Grübler** (IIASA) and started by two interventions:

- **Julia Steinberger** (University of Lausanne, Switzerland): what is sufficiency and how does it contribute to climate and well-being
- **Charlie Wilson (**University of East Anglia, UK): what is energy demand innovation and how does it contribute to climate and well-being.

These were followed by two commentaries by **Yamina Saheb** (Openex, France) and **Nuno Bento** (ISCTE-IUL, Portugal).

The discussion was very lively and a lot of contributions and ideas were collected. Sufficiency should not be understood as strict austerity, and would also need to respect inequalities and fairness. There was also a discussion on how much sufficiency is linked to political systems. LED includes both transformational efficiency solutions, i.e. many and key innovations and sufficiency aspects. LED scenarios need to respect global heterogeneity, and map energy demand aspects respective to global north vs. global south conditions and developmental needs.

It was suggested to run scenarios with more features of innovation vs. more features of sufficiency.

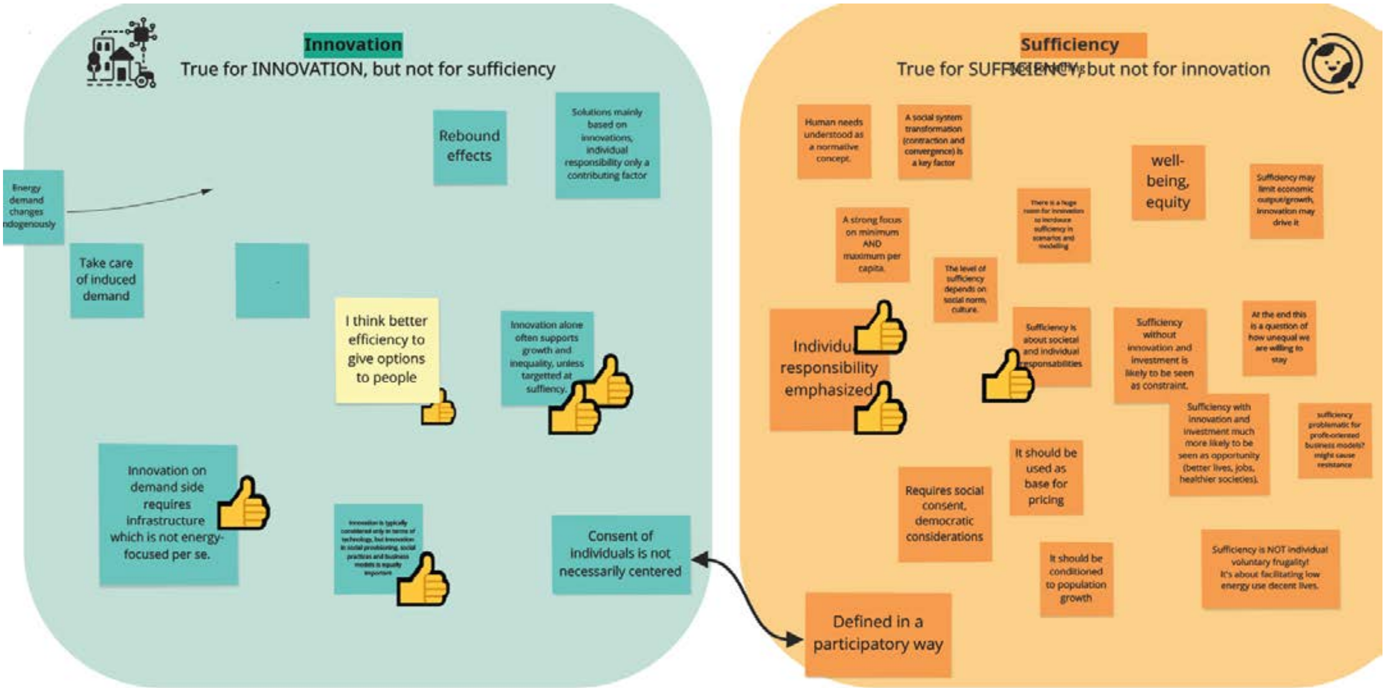


Figure 8. A snippet of the MIRO board collecting views on innovation and sufficiency

Session 4. Planning ahead

The fourth session was organized in small group moderated discussions of around 12-14 participants to understand what members of the community see as a value of EDITS for themselves and the wider research and policy community, as well as to draw up plans for the shorter and longer timeframe.

The conclusions are reviewed in the Section “Research and Outreach Plans for 2022”.

EDITS Annual 2021 Program

[All times given in CET]

December 9, Thursday

11:00-12:30 Session 1. Motivation and framing

11:00-11:10 Opening and welcome, Keigo Akimoto, RITE (Japan) and Keywan Riahi, IIASA (Austria)

11:10-11:20 Connecting science & policy: COP26 report, Joyashree Roy, Asian Institute of Technology (Thailand)

11:20-11:40 Keynote address: Energy demand modeling and policy impact for energy system transformation, John Barrett, University of Leeds (UK)

11:40-12:00 Keynote address: Operationalizing the low energy demand solutions in mobility, Sampo Hietanen, WHIM / MaaS Global (Finland)

12:00-12:30 Q&A

12:30-12:45 Coffee break

12:45-14:30 Session 2. Scientific progress in EDITS

12:45-13:45 Tour de table of Working Groups: 5-minute reports from 2021

13:45-13:55 Learning from real-life innovations for urban LED scenarios, Souran Chatterjee, Central European University (Hungary)

13:55-14:30 Breakout group discussion on the examples of real-life LED innovations and their value for EDITS

Moderated by Souran Chatterjee, Central European University (Hungary)

Building sector trends are quite persistent, cultural, technological, political and even ethical factors limit their responsiveness to change. In spite of the wide-ranging public policies and huge steps in technology innovation, the energy demand reduction potential is hardly tapped.
The session will explore a range of existing niche solutions and innovations at the social, infrastructural, technological and organizational levels. We will discuss their potential impact and how their roll-out could be analyzed and/or modelled in the scope of EDITS.

14:30-15:30 Social coffee break

December 10, Friday

11:00-12:00 Session 3. Perspectives on energy demand transformations

11:00-11:10 Kick-off statements on balancing sufficiency, efficiency and supply, Julia Steinberger, University of Lausanne (Switzerland) and Charlie Wilson, University of East Anglia (UK)

11:10-11:15 Response by Yamina Saheb, Openex (France) and Nuno Bento, ISCTE-IUL (Portugal)

11:10-12:00 Discussion on how to balance between sufficiency, efficiency, and supply: narrative development and modeling

Moderated by Arnulf Grübler, International Institute for Applied Systems Analysis (IIASA)

In many of the discussions of the EDITS network, the differences and commonalities between the sufficiency and energy demand innovation approaches have been alluded to, but we have not discussed these aspects explicitly. In this session, EDITS members are invited to identify the differences and overlap between sufficiency and innovation-driven approaches to global and local LED-type scenarios. We will discuss the implications for narratives, key modeling assumptions, scenario definitions, and policy-implications.

12:00-12:15	**Coffee break**	

12:15-13:45	**Session 4. Planning ahead**	
12:15-13:15	Tour de table in break-out groups: all participants are invited to express expectations for the EDITS 2022 goals and plans • EDITS and you: what have you/your team gained from EDITS and what are you looking forward to for next year? • Heterogeneity in EDITS work: how to move towards improved representation of Global South in membership and in the work? • Should we change the regularity and/or types of meetings? • Policy makers show interest in Demand Scenarios, what is your interest in the EDITS network's balance between research and policy impact?	
13:15-13:45	Expectations for the next year(s) of EDITS and next steps, Bas van Ruijven, IIASA (Austria)	

13:45-14:45	**Social coffee break**	

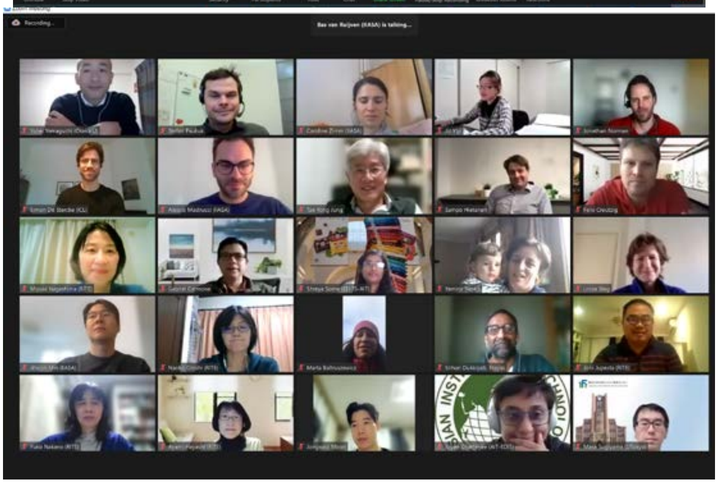
EDITS Annual 2021 Participants

The meeting had 73 participants, which is 58% of all EDITS members. Typically 50-55 people were present at given sessions at the same time.
[Data based on zoom records of participants.]

List of Participants

Alessio Mastrucci (IIASA)
Aniruddha (Prayas)
Arnulf Grubler (IIASA)
Atsuko Fushimi (RITE)
Atul@Prayas
Ayami Hayashi (RITE)
Bas van Ruijven (IIASA)
Benigna Boza-Kiss (IIASA)
Biying Yu
Camila Ludovique
Caroline Zimm (IIASA)
Charlie Wilson (UEA)
Diana Urge-Vorsatz (CEU)
Dominik Wiedenhofer (BOKU)
Elena Verdolini (CMCC)
Felix Creutzig (MCC)
María Fernanda Godoy León (Uni Ghent)
Gabriel Carmona (UCAM)
Giacomo Marangoni - Polimi/CMCC
Gregory Nemet (University Wisconsin)
Indrajit Pal (AIT-Thailand)
Jan Streeck (BOKU)
Luis Miguel Martinez (ITF)
Marianne Zotin
Marta Baltruszewicz (Univ. Leeds)
Masa Sugiyama (UTokyo)
Massimo Tavoni (CMCC)
Miyuki Nagashima (RITE)
Naoko Onishi (RITE)
Narendra Pai (Prayas)
Nuno Bento (ISCTE-IUL)
Oreane Edelenbosch (UU)
Ou Xunmin (Tsinghua University)
Pat Wagner (IIASA)
Paul Brockway (University of Leeds)
Paul Natsuo Kishimoto (IIASA)
Paula Borges da Silveira Bezerra
Poornima Kumar (CSTEP)
RITE Honjo
Roberto Schaeffer (COPPE)
Sampo Hietanen (WHIM)
Sascha NICK (EPFL)
Shimoda Yoshiyuki (Osaka University)
Shonali Pachauri (IIASA)

Jarmo Kikstra (IIASA / Imperial)
Jihoon Min (IIASA)
John Barrett (University of Leeds)
Jonathan Norman (CREDS)
Jongwoo Moon
Joni Jupesta (RITE)
Joyashree Roy(EDIt/AIT)
JU Yiyi (Univerrsity of Tokyo)
Julia Steinberger (Univ. Lausanne)
Keigo Akimoto (RITE)
Keywan Riahi (IIASA)
Leila Niamir (CMCC/IIASA()
Leticia Magalar (COPPE)
Linda Steg (Univ. Groningen)
Shreya Some (EDITS-AIT)
Simon De Stercke (ICL)
souran chatterjee (CEU)
Srihari Dukkipati (Prayas)
Stefan Pauliuk (Univ. Freiburg)
Tae Yong Jung (Yonsei University)
Talita Cruz (COPPE)
Volker Krey (IIASA)
Yamada Koya (RITE)
Yamina Saheb (Openex)
Yohei Yamaguchi (Osaka University)
Yong-Gun Kim (Korea Environment Institute)
Yuko Nakano (RITE)



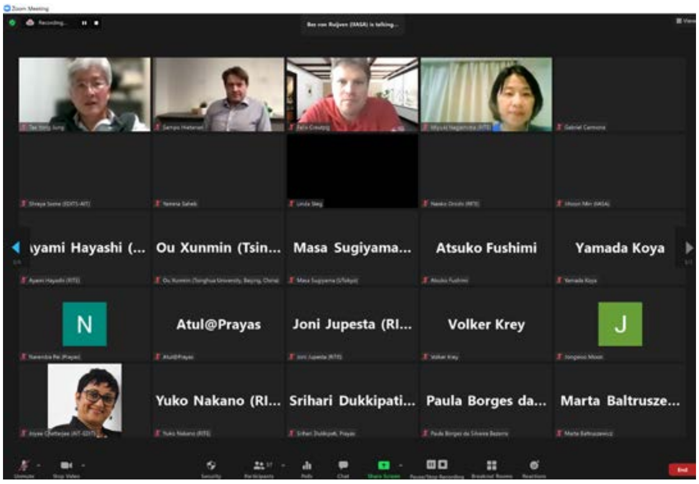


Figure 9. Screenshots of participants during the EDITS Annual 2021 meeting

EDITS Annual 2021 Social Coffee-break

The social event was organized in the platform Gather-town, which is shown below.

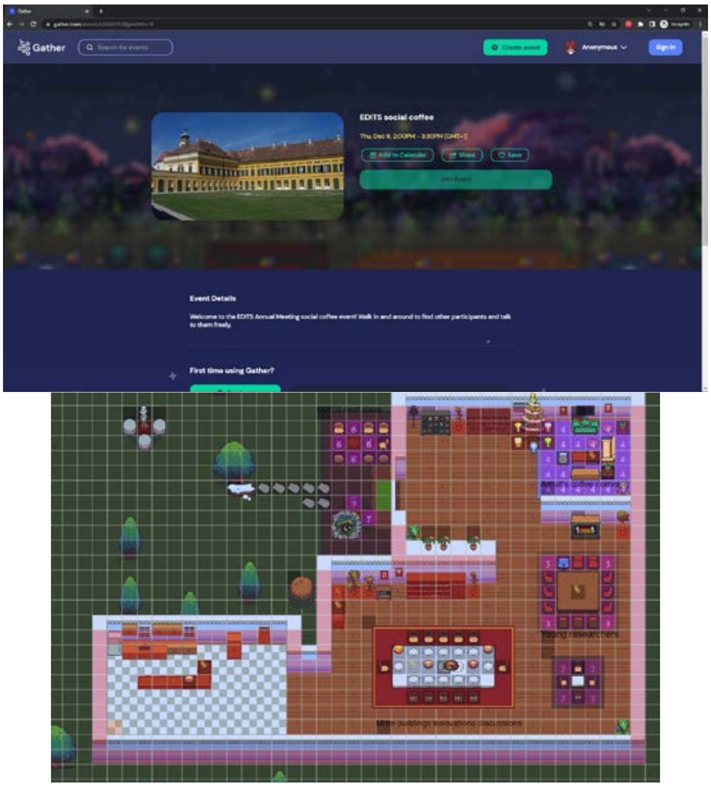


Figure 10. Screenshots from the Gather.town event

Summary Report

PART 2. Progress report 2021-2022: the current state of building sector modeling

February 2022

Submitted to

Research Institute of Innovative Technology for the Earth, Japan

International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

EDITS
Energy Demand changes Induced by Technological and Social innovations

RITE
Research Institute of Innovative Technology for the Earth

Progress report 2021-2022

V.Feb22.4 (4pages)

Researcher

Leila Niamir
Email: niamir@iiasa.ac.at
Tel: +43(0) 2236 807 257
International Institute for Applied Systems Analysis (IIASA)
Laxenburg, Austria

Leading activity

- **Co-leading EDITS WG1-Buildings**

  Key activities in 2021:

  - Regular series of bi-monthly working group meetings;
  - Designed literature review queries and prepared a database for WG members;
  - Two rounds of model's developer survey (both quantitively and qualitatively);
  - Prepared and submitted a paper précis to the Annual Review of Environment and Resources (ARER). For more information, see the main research activities below.
  - Prepared "Guideline document" to facilitate the writing ARER paper procedure and increase collaboration in the author team.

  For more information on the activities and goals of this working group, please see WG1-Buildings 2021 report and the 2022 annual plan.

Main research activities

- **Mapping demand-side models in the building sector**

  Together with 23 memebers of WG1-Buildings, we designed a research activity to investigate the state-of-the-art of energy demand modeling in the Buildings sector.

  Summary. Buildings support human activities and well-being by providing shelter and services to their occupants. Improving service provision in buildings while reducing energy demands is important for many UN Sustainable Development Goals (SDGs). The building sector has a significant climate impact, accounting for almost 40% of energy and process-related GHG emissions (Ürge-Vorsatz, et al. 2020). Demand-side mitigation strategies in buildings technically could provide 78% (6.8 $GtCO_2e$) GHG emissions reduction by 2050 (Creutzig, et al. 2021). Computer-based modeling is a powerful tool for scientists and policymakers to investigate trends and changes in building stocks and their energy demand. However, until now, there has been limited effort to model the buildings sector and its dynamics with a comprehensive view on technological and social transformations towards a low energy demand (LED) future (Grubler, et al. 2018). Representing LED scenarios and their complexity requires essential shifts in modeling practices, placing energy services in the foreground, and accounting for bottom-up elements and drivers that are not part of most models. Here we review a wide range of modeling tools to identify best practices and critical gaps in representations of a LED transformation in the building sector. We focus on the principal characteristics of LED narratives including three dimensions of interventions (socio-behavioral, infrastructural and technological) and four megatrends (digitalization, decent living, sharing economy, and circular economy). This review provides new insights on the building energy modelling landscape, the developments needed to understand LED transformation, and the linkages with other sectors and multi-sectoral models to better support decision making towards climate change mitigation and sustainability targets.

Methods. We adopt a multimethod approach combining literature review, model survey and comparative analysis, and expert elicitation and appreciation, to tackle the complexity of LED transformations of buildings and their model implementation. We use the narrative literature review techniques to review relevant literature on energy modeling in the buildings sector and LED transformation. We identify about 150 recent journal articles, narrowed down from an initial list of over a thousand publications. We develop a set of criteria to select literature relevant to LED narratives and scenarios modeling. The selected literature spans from regional to global geographical scope, covers both global north and south, and consists of both impact assessment and forward-looking scenario studies using building sector-specific or multisectoral models. We focus specifically on models that are strong in representing the demand-side of the buildings sector and have or foresee running LED scenarios. We conduct a detailed survey and comparative analysis of 13 models representative of diversity across representation and solution algorithms. We use a dedicated questionnaire in combination with interviews with expert modeling teams to investigate the scope, features, and potential of existing models to capture the future dynamics and impacts of LED transformations. Building on the experience of the EDITS (Energy demand changes induced by technological and social innovations) research network, we discuss the results of the literature review and model comparative analysis in a series of expert elicitation workshops to identify modelling gaps, needs, and best practices.

State of the art in buildings energy modelling. Based on the literature review, we provide an overview of the current and emerging buildings energy modelling landscape. We categorize the identified models based on their purposes and aims, their methodological approaches, their sub-sector, end-use, geographical, and temporal focus, and level of disaggregation. We claim that diverse types of models are complementary, rather than competitive in their ability and value to represent LED futures in the buildings sector.

We investigate three dimensions of a LED transformation: socio-behavioral, infrastructural and technological interventions. Socio-behavioral interventions covered in this work include energy-saving practices, behavioral and lifestyle changes. Infrastructural interventions relate to urban design and forms, such as compact cities, and building floorspace reduction. Technological interventions involve net-zero and passive energy building construction and retrofits, smart buildings, energy efficient appliances, dematerialization, and digital convergence. For each of these dimension, we explore trends and strategies towards significant energy demand reductions, informed by experts' knowledge. By reviewing best practices, we identify: a) what kind of LED dynamics are represented in models and how are they implemented?; b) what are the current critical modelling gaps for understanding LED futures?; and c) what key drivers and elements need improved representation?

In addition, we analyze a set of four cross-cutting megatrends driving the LED narrative and so expected to play a key role in energy demand reduction: digitalization, decent living standards, sharing economy, and circular economy. After investigating the connections with the LED interventions above, we focus on best practices and gaps in modeling these megatrends. For digitalization, we include the introduction of building automation systems and smart meters, and work-from-home practices accelerated by the COVID-19 pandemic. We discuss the representation of access to decent living standards (Rao & Min, 2018), in particular access to decent housing and energy. Sharing economy practices addressed in this work include building sharing (e.g., co-housing and co-working), flexible usage, appliances and services sharing. For circular economy, we analyze the representation of building design, materials choices, lifetimes of buildings, refurbish & repair versus demolition.

Novelty of this work. Our study discusses critical bottlenecks limiting the development of LED scenarios for the buildings sector, a development that is timely in view of the urban net-zero targets. The innovative contribution of this work is threefold:

- *Low energy demand interventions in the buildings sector:* we identify and expand on the three main types of intervention for transitioning to low energy demand in the buildings sector: 1) socio-behavioral; 2) infrastructure; and 3) technology;
- *Mapping buildings energy demand modeling:* by reviewing literature, surveying models, and conducting interviews, we identify gaps in model coverage, granularity and heterogeneity, model dynamics, and linkages across sectors and models. We identify key model gaps in: the representation of service level provision, the role of buildings as shelter, novel lifestyle and business changes that drive the sector. In addition, for models to provide a comprehensive picture of the whole sector there are gaps in the representation of the non-residential sector, developing countries, linkage between actors, infrastructures and technologies. We show how models alone cannot and should not include all LED aspects, but should be strong in detailed representation of given drivers and form a complete picture via model-interlinkages. We describe this as complementarity.
- *Beyond buildings, cross-sectors and cross-cutting themes:* the domain of this study is not limited to the building stock and dynamics. We go beyond that by studying: 1) the ecosystem and cross-sectors themes, particularly looking to human settlement, urban design, and interlinkages to mobility and transport, and industry; 2) the cross-cutting themes and mega-trends, such as digitalization, decent living standards, and sharing and circular economy.

The paper précis is submitted and under review of a high impact factor journal, Annual Review of Environment and Resources (ARER). The aim is to submit the full paper in Summer 2022.

- **LED Narratives**

  Together with Gregory Nemet and Elena Verdolini, we have worked and drafted a paper on "Social and Technological Innovation Pathways for Low Energy Demand", where I have been leading the research on social innovation and behavioral interventions. This research activity is summarized in a report delivered by Gregory Nemet, under *EDITS WG3-Narratives.*

  We aim to submit the full paper to a high-impact journal in Summer 2022.

- **Modelling low-carbon energy demand pathways**

  I have been working on a (sole author) perspective paper. In this paper, I argue there is a huge gap between climate stabilization scenarios and the reality of decision-making. In other words, the existing modeling approaches fail to provide policy-relevant energy demand-side mitigation scenarios that take agency seriously. In this perspective, drivers of change in the transition to low-carbon energy demand are comprehensively assessed, and a modular architecture modeling framework is proposed that enables spatially and contextually explicit consideration of policies and their dynamic potential to reduce greenhouse gas emissions.

The perspective synopsis is already submitted to Nature. The aim is to submit the full paper in April 2022.

Other activities

- **Within EDITS Community**
  - Collaboration with *EDITS WG1-Industry* on the review paper, particularly under section 4, agent-based modeling
  - Collaboration with *EDITS WG1-Transport* on the review paper with interests in behavioral and social aspects of mobility; link to infrastructure and building sector (urbanization)
  - Collaboration with *EDITS WG2- Data* on the review paper, providing data on energy demand potentials over end-use sectors

- **Conferences**
  - Organizing a symposium entitled "Energy Demand Transition: Changes Induced by Technological and Social Innovations" at the International Conference on Energy Research & Social Science, 20-23 June 2022, Manchester-UK

  - Co-organizing a session entitled "Narratives for scenarios and pathways to provide decent levels of energy services at low demand of energy and resources" at the Scenario Forum 2022, 20-22 June 2022, Laxanburg-Austria

（様式２）

二次利用未承諾リスト

報告書の題名　令和３年度地球温暖化対策における国際機関等連携事業委託

委託事業名　技術革新によるエネルギー需要変化に関するモデル比較国際連携事業

受注事業者名
公益財団法人　地球環境産業技術研究機構

頁	図表番号	タイトル
473-495	Annexure IV (スライド)	⑩Asian Institute of Technology (AIT)「Final Report」
496-497	Annexure V (表)	⑩Asian Institute of Technology (AIT)「Final Report」
498-499	Annexure VI (スライド)	⑩Asian Institute of Technology (AIT)「Final Report」
529-543	全ページ	⑪University of Groningen「Promoting reductions in fossil energy demand」
652	「National data center energy statistics」(7段落)	⑬University of California, Santa Barbara 「Technology datasets for modeling the energy demand of data centers」
652	「National data center energy statistics」(8段落)	⑬University of California, Santa Barbara「Technology datasets for modeling the energy demand of data centers」
735-750	全ページ	⑯東京大学「Preparatory study for a model complementarlity exercise on demand-side innovations for climate change mitigation」