令和４年度

気候変動対策に係る国際会議の開催等によるエネルギー・環境技術

イノベーション創出のための国際連携推進事業

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５年３月

公益財団法人 地球環境産業技術研究機構

令和４年度 気候変動対策に係る国際会議の開催等によるエネルギー・環境技術イノベーション創出のための国際連携推進事業
（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）

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、２０２１年に行われたCOP26の場等においてもその解決、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る。

最近の国内外の動きとしては、２０１５年末の気候変動枠組条約第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、２０１８年１２月に、ＣＯＰ２４において、市場メカニズムの合意によりパリ協定実施指針が完成したことを受けて、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する。特に、２０２２年は、２０２３年に実施予定の第1回グローバルストックテイクに向けた方法論を議論する年であり、パリ協定の目標に向けた各国の気候変動対策の進捗やNDC達成に向けた実現可能性などについて、議論が深められてきているところである。

また、150以上の国と地域が、21世紀中ごろ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、各国の気候変動対策が急速に進む中で、各国・各地域・各産業の状況を総合的に考慮するとともに、気候変動政策の立案に貢献し得る様々な評価・分析を行う重要性は一層高まってきた。

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。また、第６次評価報告書では、新たにエネルギー需要サイドの評価を扱う章が設けられるなど、国際的に注目された。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。ＩＰＣＣにおいては、第６次評価報告書が順次公表され、2022年4月には第３作業部会（緩和）の報告書が、そして2023年3月には統合報告書が公表され、第６次評価報告書のプロセスは終了した。一方、とりわけ需要サイドの分析・評価については多くの研究課題が残っており、第７次評価サイクルに向けても、気候変動に関する最新の科学的知見の提供が求められ、それに貢献していくことが重要である。従って、経済と環境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の重要性は極めて高い。

本事業は、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き、今後のＩＰＣＣ報告書等へインプットしていくことを目的に実施した。

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ＣＯ２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一覧参照)

（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、評価を行う。加えて、ＬＥＤシナリオの国際研究コミュニティにおける位置づけを主流化できた。

（詳細については各研究機関の報告書を参照）

①RITE 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、ナラティブグループが暫定的に策定した High with Low (HwL)シナリオに沿った形で、特にデジタルトランスフォーメーション（DX）によって誘発され得るサーキュラーエコノミー、シェアリングエコノミー（運輸におけるライドシェアリング、カーシェアリング、バーチャルミーティング、E-publication、食品ロス低減、3D プリンティング等）に焦点を当て、世界エネルギー・温暖化対策評価モデル DNE21+を用いた定量的な分析結果を一次試算として提供した。これによって、今後の EDITS 全体としての定量的なシナリオ分析の方向性を提示した。

②米国ローレンスバークレー国立研究所 (LBNL)は、低エネルギー需要シナリオのモデリングのために技術的および社会的イノベーションの定量的コストと市場採用データをまとめて評価した。また、需要側イノベーションの採用増加における政策とプログラムの影響要因と役割の評価を実施した。

③中国清華大学は、以下を含む中国における高速鉄道計画の影響を考慮した民間航空の低炭素開発経路に関する分析を行った。

・フリートの視点に基づく民間航空分析フレームワークの確立。

・高速鉄道開発の文脈における、ほぼゼロ排出という目標に向けた民間航空の最適な開発経路。

・主要な時点における水素動力航空機やバイオマス燃料などの主要な低炭素技術のスケール。

・水素価格などの重要な要因が民間航空産業の発展経路に与える影響。

④タイAIT は、EDITS -AITプロジェクトレポート-フェーズIIIとして、南アジア諸国での活動報告をまとめた。また、急速に成長する南アジアの経済におけるセクター別およびインフラストラクチャ開発について研究し、バングラデシュを例に成長経済のエネルギー部門の持続可能性評価を行った。
⑤東京大学は、新たなモデル相互比較の設計と実施のコーディネーションを行った。
⑥ブラジルCOPPE は、統合評価モデルの庇護の下で、1.5 度への道のりで産業界によってもたらされる世界的および地域的な機会と制約を解説した。
⑦韓国延世大学他は、低エネルギー需要のシナリオと、GDP、福祉、国際貿易におけるカーボンプライシングと将来のエネルギー需要に関する世帯特性の評価を行った。
⑧米国ウィスコンシン大学マディソン校は、1) 公平性とアクセス、2) デジタル化、3) イノベーションに3つに焦点を当てたワーキング グループ 3「ナラティブ」に基づく活動と3)イノベーションの研究努力から得られた知見を紹介するとともに、低エネルギー需要の促進とそれに役立つ政策手段に焦点を当てた2023年のグループ3の活動支援となる分析を実施した。
⑨米国スタンフォード大学は、2021 年と 2022 年に他の主要な研究機関によって作成されたEDITSシナリオの比較評価を行った。
⑩大阪大学は、日本の民生部門におけるエネルギー需要動向、要因および変化等に関し、その定量的な分析を含めてとりまとめを行い、EDITSから得られるシナリオを反映した将来予測を行った。
⑪ITF-OECD は、EDITS ネットワークで使用されるモデリング ツールと出力に関する概要を紹介し、1)ITF グローバル非都市旅客、2)グローバル貨物および3)車両フリート モデルの更新された方法論や運輸部門に対する EDITS ベースの低エネルギー需要シナリオの影響のテスト結果を報告した。また、EDITS コミュニティの他のモデルと互換性のある 1つのデータセットで、低エネルギー需要現象に対する輸送需要の感度分析を提供した。
⑫イタリアCMCC は、エネルギー集約型産業部門における 3D 印刷と低エネルギー需要に関する研究、住居施設の資源(電気、天然ガス、および水)使用の波及、望ましいLEMD シナリオなどをとりまとめた。
⑬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、低エネルギーおよび材料需要シナリオのためのシステム全体の業界モデリング アプローチのレビューを実施した。
⑭英国オックスフォード大学は、デジタル消費者イノベーションがエネルギーと炭素排出量に与える影響を評価した。
⑮ハンガリーの中央ヨーロッパ大学は、建物に統合された太陽エネルギー (BISE) モデルを基に、2060年まで 11 地域ごとに年間および時間単位の解像度で建物に統合された太陽エネルギー生産の可能性の調査を行い、世界中の建築部門における潜在的なカーボン ロックイン効果を計算および分析を実施した。また、建築部門における2060 年までの世界各地域で熱エネルギー需要に対する正味ゼロの可能性を調査した。
⑯オランダのユトレヒト大学は、低エネルギー需要経路の説明を改善するために克服する必要がある主要なデータ ギャップのレビューを実施した。

⑰ポルトガルのリスボン大学研究所は、技術変遷の形成と衰退の歴史的ダイナミクスについて取りまとめた。
⑱オランダのフローニンゲン大学は、低炭素生活の評価を行った。
⑲IIASA は、LED シナリオと WS サマリーを表す建築セクター モデリング ツールの現状を含むサマリーレポートをまとめた。また、8月に開催したWS について、研究動向など主要な内容を整理した。
⑳米国カリフォルニア大学は、デジタル化を促進するエネルギー需要のグローバル データ通信ネットワークをモデル化のため、利用可能な最良のデータのレビューととりまとめを行った。

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う。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13名、WG3 SPM執筆者15名）ており、今後のIPCC 報告書等、国際的な研究への影響が大きいと考えられるワークショップとなった。

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たが、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、LindaSteg氏、Charlie Wilson氏は執筆協力者である（なお、今回のワークショップは欠席となったが、その他、第5章代表執筆者のGregory Nemet氏、Julia Steinberger氏もEDITS事業には貢献している）。

（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）や（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オーストラリアのラクセンブルクコンファレンスセンターで開催し、エネルギー需要部門の分析に関する情報交換、研究内容の共有行った。詳細については次頁以降に示す。なお、その他、４半期に１回オンライン会議によっても、エネルギー需要部門の分析に関する情報交換、研究内容の共有行った。

【会議報告】

2022 Annual EDITS Meeting
Transformation to high wellbeing with low energy demand

2022年 8月30～9月1日
ラクセンブルク カンファレンス センター、オーストリア

背景

技術的および社会的イノベーションによって引き起こされるエネルギー需要の変化 (EDITS) は、需要主導のエネルギーシステム、エネルギーおよび技術-社会-インフラの相互作用中心の材料需要予測をグローバルと詳細なレベルで、またウェルビーイングと SDGs との関係において理解を深めるために 2019 年に開始した。EDITS コミュニティは、需要側のソリューションとエネルギー システムの変革に関するモデリング、実証分析、コミュニケーションを強化するためのギャップと可能性を特定するため共同研究を追求している。

EDITS コミュニティは、建物、輸送、産業の 主要 3 セクターでモデル マッピングに取り組んできた。データの可用性とギャップの特定に取り組み、需要関連データを管理するためのフレームワークを定義している最中である。ナラティブ グループは、新しい LED タイプのシナリオである「High-with-Low」シナリオを提案し、それを DETRAS モデル (別のプロジェクトの一部として開発された) とリンクさせ、「High-with-Low」シナリオの理解に取り組んだ。並行して、EDITS Model Complementarity Protocol ワーキング グループはテスト フェーズを完了し、「High-with-Low」シナリオのクロスモデル演習の準備を行った。全体像を完成させるために、多次元の福祉と実現可能性のフレームワークを現在開発中である。

概要

2022 年のワークショップは、国際応用システム分析研究所 (IIASA) と地球環境産業技術研究機構 (RITE) が共催で行った。 会議は、本事業開始後は、COVID-19 パンデミックによって 2 年間、オンライン開催となっていたが、ウィーン (オーストリア) に近いラクセンブルクにおいて対面で開催した。オンライン接続は、ハイブリッド セットアップなしで Zoom を介して提供され、主に個人的な理由 (例: COVID-19 感染) で直前に出席をキャンセルした人々の参加を可能にした。 会議には、79 人の直接参加者と 6 人がオンラインで参加した。 参加者は、モデラー、社会科学者、経済学者、エンジニアなど、さまざまな分野の専門家であった。 議論の流れを確実にし、将来のコラボレーションの定義に注意を払うために、参加者は招待制であった。参加者詳細は、以下を参照。

以下の通りに 3 日間、9 セッションで構成された。



Figure 1. The EDITS 2022 Annual Meeting set-up.

Table 1 Sessions

Session	Contents
1	How local can we go?
2	Parallel Working Group sessions
2a	Working Group 3 – Narratives
2b	Working Group 1 – Buildings
3	How to sell a low energy demand scenario?
4	Parallel Working Group sessions
4a	Working Group 3 – Model complementary protocol
4b	Working Group 1 – Transport
5	Fast-track proposals
6	Research presentations of the community
7	Parallel Working Group sessions
7a	Working Group 1 – Industry
7b	Working Group 3 – Synthesis
8	Multiple dimensions and benefits of demand side
9	Closing plenary with break-out groups

EDITS の年次会議は、共同研究とモデリングの基盤である。 会議は、一方では、深い議論を組み合わせるためのフォーラムを提供し、他方では特定のワークフローを強化するため場所を提供した。

会議の目的

本会議と分科会(ワーキンググループ)は、 (1) グローバルな LED ナラティブを多様なサブグローバルな文脈に関連させるために何が必要か、(2) LED のシナリオをより良く提示し、伝達する方法、(3) LED の未来に向かうことの利点は何か、を含むトピックに関する対話プラットフォームを提供した。

各ワーキンググループには、進行中または今後の作業を進めるための専用のセッションがあり、作業段階に応じてセッションを使用した。上記のように、ワーキンググループは 2021 年から 2022 年間にテスト フェーズと準備を完了し、各グループがワークショップで発表を行った。これらに基づいて、ワークショップは、さらなる研究成果に向けて前進するため、次の作業の流れを特定するプラットフォームとして機能した。

また、個人およびチームにより EDITS と関係したエネルギー需要に関連する研究を紹介する特別セッションも開催した。セッション 5 (Table 1)では、小規模な内部グループが特定のトピックに取り組むためのアイデアを募集した一方、セッション 6 では、EDITS メンバーが EDITS の一部または外部で実施する研究で、コミュニティにとって興味深いと思われる研究を共有した。

会議内容

1. 主な議論内容

EDITS 研究の役割と、コミュニティの焦点

- 気候危機の緊急性と、その他の圧力 (戦争、パンデミック、経済的および社会的苦痛など) の増加により、研究コミュニティは、研究のギャップを埋めて前進するよう、より多くの圧力を受けている。
- 今日の課題は複雑で、体系的な視点が必要である。需要側のアプローチは、詳細な人間中心のソリューションをより適切に提供することができるが、体系的なレベルも考慮し、(SDG に沿った)適切なレベルのウェルビーイング、地球システムの境界、全国平均の代表的な消費者または世帯を超えた不均質性を反映する分布の側面、およびサービス提供システムに影響を与える制度的/組織的変数のために必要なリソース量を理解する必要がある。エネルギーと資源の需要自体が中間変数であることを強調することが重要である。
- IPCC により、実際の人間のウェルビーイングを測定するためのより良い測定基準、デジタル経済の気候への影響の評価、サービスのシナリオモデリング、変化のさまざまな要因間の相互作用（社会的、 構造的、個人的）など、EDITS 関連の研究におけるギャップがいくつか特定された。

グローバルな LED のナラティブを多様なサブグローバルな文脈に関連させるために何が必要か

- High with Low future (HwL) ナラティブの説明
- HwL には、インプット指向の分析からアウトプット指向 (サービスとウェルビーイング) アプローチへの移行が含まれる。
- HwL は、サービス、人々とウェルビーイング、未来を想像するための高度に分散された分散型アプローチ、相互依存行動、社会イノベーション、制度的イノベーション、技術イノベーションに重点を置いている。

- 変換効率と技術的パフォーマンスに焦点を当てる代わりに、HwL はサービス効率（デバイスの収束）に注目する。 それは、イノベーションが行動、ビジネスモデル、制度全体をどのように変えていくかである。

低エネルギー需要シナリオを売り込むには? (LED シナリオをうまく提示して伝達する方法)

- さまざまな聴衆向け言葉遣い: 肯定的な言葉遣いは、より共感を呼び、より多くの支持を得る傾向がある。しかし、ソブリエテに関するフランスの経験は、公共のエネルギーに関する議論が需要削減の議論に前進することを可能にしたことを示している。また、規範的で学術的な文言は、一般大衆に届くようにするために避けるべきである。政策立案者にとっては、シナリオの結果を数値で提示する方が効果的である。
- 需要の変化を可能にするための戦略: ソーシャル メディアは、気候変動がすでに起こっていることを知らせ、私たちに何ができるかを伝える重要なツールである。高い需要を誘発するために企業の力や資源と競合することはできないように思われるかもしれないが、需要削減の議論を可能にする政治的背景を作り出すことが重要である。
- 受容性と意欲: 気温上昇制約に関する戦略が効果的であるという確信は、技術の変化よりも行動の変化/需要の削減をより受け入れやすくする。 また、気候の緊急事態に対する懸念は、LED シナリオの受け入れ可能性を高めることにつながる。 ただし、LED のナラティブの受容性は高いかもしれないが、ライフスタイルの変化の観点からシナリオの説明が行われる場合はそれほどではない。
- 多様性と不平等の考慮: 文化の多様性と不平等は、異なる状況にいる人々は異なるニーズを持っているため、需要側の変革のメッセージを構成する際に考慮されるべきである。

需要側の複数の側面と利点 (LED の未来の価値をさまざまな観点からの検討)

- High with Low シナリオでは、持続可能な開発を LED の拡張によるエントリ ポイントとして使用し、LED よりも高い空間解像度で選択されたレバレッジ フォーカス（DSL、デジタル化、イノベーション）を選択する。影響評価（水、土地、空気）と実施の焦点（都市、経済、インフラ）を拡大するために、HwL にさらに取り組む必要がある。
- EDITS シナリオの最終的な目標は、統合シナリオを作成することである。よって、次のことが必要である: 運用コンセプトとウェルビーイング次元の測定値の開発、分布の表現/モデリングの開発、気候を超えた惑星の境界の明示的考慮、社会的および制度的側面を含める、代替経路の探索
- 健康と生産性は、グローバルなメリットではなく、ローカル レベルでのメリットである。
- エネルギー安全保障とエネルギー需要削減の役割との間には強い関連性があり、ネルギー需要を削減することで、世界の排出量を 12 ヶ月で 2.9% 削減し、燃料不足を回避できる。
- IPCC は、マクロ経済レベルでのコベネフィットとトレードオフは過小評価されており、緩和戦略では考慮されていないと結論付けた。
- 主なコベネフィットは、**雇用、貿易、構造変化**として特定された。多くの場合、雇用創出はエネルギー需要部門からの方が高い。

- 競争力/環境に配慮した構造変化への**緩和の影響を評価するための新しい指標**が必要である。

2. ワーキンググループ

- ナラティブグループ - High with Low についての説明、DETRAS フレームワークを使用した一貫した需要の定量化についての議論、ワーキンググループ（建物、運輸、産業）の座長間の情報共有と議論、建物の需要を中心とした議論
- 建物グループ - 次の作業段階の計画と起草。 事前に提出されたトピックは、各 5 分でメンバーによって提示され、これらの研究案はその場でさらに発展させられ、拡張された概要と関心のある貢献者のリストに追加された。
- 運輸グループ -WG プロトコルチームとの議論、現在進行中のペーパー ドラフトは拡張され、サブセクションは小グループで議論を行った。 目的は会議の直後に論文の草案を完成させることである。したがって、このセッションの終わりまでに、サブチャプターの責任者が特定され、草案の内容も議論した。
- 産業グループ - 文献収集とコーディングの第 2 ラウンドの結果について、すべての共著者の協力を得て議論し、改良を行った。 モデルファミリーの概要と文献に残っているギャップが特定され、責任が割り当てられ、追加の専門家が貢献するよう招待された。 レビュー ドラフトの既存の構造と内容について議論し、10 月または 11 月に開催される次回の WG 会議に向けて詳細なロードマップの準備を行った。
- プロトコルグループ –テスト フェーズのプレゼンテーションと、補完性演習のプロセスの提案。指標リストと従うべきプロセスについて議論。 産業と建物の 3 つの小グループに分かれて詳細な議論を行い、輸送はセッション 4.b に統合された。 締め切り、タスク、および活動リストについての説明を行った。
- 統合グループ -ウェルビーイング/実現可能性分析の理論的フレームワークを提示し、さまざまなウェルビーイングの次元の重要な指標を導出するための潜在的な方法論について議論し、選択した指標とモデルを提供する可能性について EDITS コンソーシアムからこれらのインジケーターを構築するために必要な出力/変数のフィードバックを求めた。
- データグループ - アイデアと関心の収集を行い、データギャップのレビュー構造に関する発表、いくつかの明確な実例に取り組むことによるインタラクティブなディスカッション + 次のステップのレビュー ペーパーの策定などを行った。

3. ポスター発表

EDITS の活動は、メンバーの通常の研究関心と密接に関連している。 EDITS の価値は、実行中の研究をより広い視野で組み合わせ、新しい概念、斬新なアイデア、再構築された方法を見つけることにある。ここでは、コミュニティの研究発表会として、コミュニティ全体に関連するメンバーの進行中の内部調査を紹介した。スピーカーはそれぞれフラッシュ トークで研究を発表し、続いてポスターが掲示している場所にて、さらに興味のあるオーディエンスと議論を行った。

ポスターの発表者は以下の通り:

- Yekatherina Bobrova, George Papachristos (Uni of Oxford, Eindhoven University)
- Yekatherina Bobrova, Nick Eyre, Tina Fawcett, Colin Nolden, George Papachristos (Uni of Oxford, Eindhoven Uni)
- Ayami Hayashi, Takashi Homma, Keigo Akimoto, Fuminori Sano (RITE)
- Arnz Marlin, Alexandra Krumm, Philipp Blechinger (Technical Uni. Berlin; Uni. Flensburg; RLI)
- Sascha Nick, Joel Millward-Hopkins, Julia Steinberger, Philippe Thalmann (EPFL, University of Lausanne)
- Sascha Nick, Philippe Thalmann (EPFL)
- Bianka Shoai-Tehrani, Gersende Chaffardon, Jean-Baptiste Arnoux, Gaëlle Lestage, Emeric Benoni, Pascal Gibielle (RTE)
- Johannes Thema, (Wuppertal Institute for Climate)
- Yohei Yamaguchi, Hideaki Uchida, Yoshiyuki Shimoda (Osaka University)
- Caroline Zimm, Paul Kishimoto, Setu Pelz (IIASA)
- Hara Takuya (IIASA, Toyota)
- Naoko Onishi, Joni Jupesta, Fuminori Sano, Keigo Akimoto (RITE) [online]
- Albane Gaspard (ADEME) [online]

4. ファーストトラック案

興味深くも焦点を絞ったアウトプットにすぐにつながる可能性のある関心領域を特定するために、アイデア募集が発表された。バス・ファン・ライベン氏は、ファスト トラック イニシアチブの迅速な完了をサポートするための計画を提示した。 少人数のメンバー グループを率いて、焦点を絞ったレビュー/調査/要約/斬新な成果物（ブログ、ポッドキャストなど）の提供の可能性について検討した。

以下の 4 つの提案が提出、発表された。

- チャーリー・ウィルソン氏: デジタル化のモデル化
- 杉山 昌広氏，タオ・カオ氏、イーイー・ジュ氏、バス・ファン・ライベン氏: 高レベルのウェルビーイングと低エネルギーおよび材料のための改善された需要側モデリング。
- サーシャ・ニック氏: 負の排出が社会に利益をもたらす保証
- ベニグナ・ボザ-キッス氏とヌーノ・ベント氏: サービスのセキュリティと低エネルギー需要

ファーストトラック チーム（年次会合で提示した 4 つ以外も含めて）は、初期アイデアを 1 ページの資料で提出し、12 月の四半期で進捗状況を紹介することとした。（その後、2023 年 1 月に RITE と IIASA の研究者による評価委員会を設け、EDITS として研究推進するテーマを決定した）

付表 1 国際ワークショップの参加者リスト

	国	組織名	参加者名	IPCC 関係者

1	Japan	Ministry of Economy, Trade and Industry (METI)	Mariko Takatani	
2		Research Institute of Innovative Technology for the Earth (RITE)	Keigo Akimoto	Ch.17 LA *
3			Ayami Hayashi	
4			Joni Jupesta	Ch.17 LA
5			Naoko Onishi	
6			Atsuko Fushimi	
7		University of Tokyo, Institute for Future Initiatives (UTokyo IFI)	Masahiro Sugiyama	Ch. 12 LA
8			Tao Cao	
9		Waseda University	Yiyi Ju	
10		Osaka University; Urban Energy System Lab.	Yoshiyuki Shimoda	
11			Yohei Yamaguchi	
12	Austria	International Institute for Applied Systems Analysis (IIASA)	Arnulf Grübler	Ch.5 LA
13			Keywan Riahi	Ch.3 CLA *
14			Bas van Ruijven	
15			Benigna Boza-Kiss	
16			Elina Brutschin	
17			Fei Guo	
18			Jarmo Kikstra	
19			Paul Kishimoto	
20			Volker Krey	Ch.4 LA *
21			Florian Maczec	
22			Alessio Mastrucci	
23			Jihoon Min	
24			Leila Niamir	Ch.5 CS *
25			Mel George Vallimyalil	
26			Jin-Xiao Tan	
27			Shonali Pachauri	Ch.2, LA *
28			Narasimha Rao	
29			Caroline Zimm	
30			Setu Pelz	
31			Pat Wagner	
32			Silvia Artuso	
33		IIASA/ Toyota Motor Company	Takuya Hara	

34		Futuregram	Hernandez Flores Daniela	
35			Adriana Hernandez Flores	
36			Filippo Rezzadore	
37		Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna (BOKU/SEC)	Dominik Wiedenhofer	
38			Jan Streeck	
39		Institute of Social Ecology (SEC)	Barbara Plank	
40	France	Agence de la Transition Ecologique (ADEME)	Albane Gaspard	
41		négaWatt Association	Yves Marignac	
42		International Transport Forum (ITF/OECD)	Luis Martinez	
43			Orla McCarthy	
44		University of Lausanne (Sciences Po Paris and OpenExp)	Yamina Saheb	Ch.9 LA *
45		Réseau de Transport d'Electricité (RTE)/Economic and Environmental Studies	Bianka Shoai-Tehrani	
46	UK	Environmental Change Institute, University of Oxford (ECI/CREDS)	Yekatherina Bobrova	
47		Department of Civil and Environmental Engineering, Imperial College London (ICI)	Simon De Stercke	
48		Environmental Change Institute, University of Oxford (ECI)/IIASA	Charlie Wilson	Ch.5 Contributing Author
49		University of Oxford	Poornima Kumar	
50		University of Leeds	Joel Millward Hopkins	
51	Italy	Euro Mediterranean Center on Climate Change (CMCC), European Institute for the Economics and the Environment (EIEE)/Politecnico di Milano (POLIMI)	Pietro Andreoni	
52			Massimo Tavoni	Ch. 3 LA
53			Elena Verdolini	Ch.16 LA *
54	Germany	Workgroup for Infrastructure Policy (WIP), Technical University Berlin/RLS Graduate School, Reiner Lemoine Institute	Marlin Arnz	
55		Europa-Universität Flensburg	Luisa Cordroch	
56			Frauke Wiese	
57		Mercator Research Institute on Global Commons And Climate Change (MCC)	Felix Creutzig	Ch.5 CLA *
58		e-think energy research	Andreas Müller	
59		Oeko-Institut	Carina Zell-Ziegler	

60		Wuppertal Institute for Climate, Environment and Energy, Energy Policy Research Unit	Johannes Thema	
61	Belgium	Ghent University; Sustainable systems engineering (STEN)	Maria Fernanda Godoy Leon	
62	Portugal	DINÂMIA-CET of ISCTE-IUL (ISCTE-IUL)	Nuno Bento	
63	Hungary	Central European University (CEU)	Souran Chatterjee	
64			Diana Urge-Vorsatz	Vice Chair, Ch.8 RE *
65	Netherlands	International Research University - Universiteit Utrecht (UU)	Oreane Edelenbosch	
66		University of Groningen	Linda Steg	Ch.6 LA *
67	Switzerland	EPFL Laboratory of Environmental and Urban Economics (EPFL)	Sascha Nick	
68	India	Center for Study of Science, Technology and Policy (CSTEP)	Kaveri Ashok	
69			Ravishankar Krithika	
70		Department of Humanities & Social Sciences, Indian Institute of Technology Madras	Sabuj Mandal	
71	Thailand	Asian Institute of Technology (AIT)	Joyashree Roy	Ch.5 CLA *
72			Muhammad Huzaifa Butt	
73			Joyee S. Chatterjee	
74			Shreya Some	TSU *
75	South Korea	Yonsei University	Tae Yong Jung	Ch.15 CLA *
76			Dahyun Kang	
77			Jongwoo Moon	
78		Korea Environment Institute (KEI)	Yong-Gun Kim	Ch.2 LA
79	USA	Lawrence Berkeley National Laboratory (LBNL) - Building Technology and Urban Systems Division/Net Zero World Action Center (NZW)	Nan Zhou	Ch.4 LA
80		University of California; Columbia University (ITS-Davis; CGEP)	Pierpaolo Cazzola	
81		University of California, Santa Barbara (UCSB)	Eric Masanet	Ch.3 CA, Ch.5 LA, Ch.16 CA

82		Oak Ridge National Laboratory/International Institute for Applied Systems Analysis (ORNL/IIASA)	David McCollum	Ch.3 CA, Ch.6 CA, TSU*
83		Princeton University	Pooja Ramamurthi	
84	Brazil	Economia da Energia do Programa de Planejamento Energético da COPPE/UFRJ	Roberto Schaeffer	Ch.3 CLA *
85			Marianne Zanon Zotin	

* AR6 SPM author

各研究機関報告書一覧

	タイトル	研究所・大学	著者
①	デジタルトランスフォーメーションによるサーキュラー・シェアリングエコノミーによって誘発され得る低エネルギー需要社会とCO2 排出削減に関するコンピュータモデルを用いた包括的かつ定量的な分析・評価	地球環境産業技術研究機構	RITE
②	Assessment of Market Adoption and Cost Data, and Supporting Policies for Technological Innovations to Reduce Energy Demand [要旨のみ公開]	Lawrence Berkeley National Laboratory International Energy Analysis Department	Nina Khanna, Hongyou Lu, Michelle Johnson-Wang, Jingjing Zhang, Nan Zhou
③	A study on the low-carbon development path of civil aviation considering the impact of high-speed rail planning in China	Tsinghua University	Xunmin Ou, Zhiyi Yuan, Lei Ren, Jianzhe Liu
④	Energy Demand changes Induced by Technological and Social innovations (EDITS)-AIT Project Report- Phase III [一部のみ公開]	Asian Institute of Technology (AIT)	Joyashree Roy
⑤	Model complementarity 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, Tao Cao

⑥	Global and regional opportunities and constraints posed by the industrial sector on the path to 1.5 degrees under the aegis on an integrated assessment model	The Universidade Federal do Rio de Janeiro, Fundação COPPETEC	Marianne Zanon Zotina, Letícia Magalara, Luiz Bernardo Baptistaa, Gabriel Cardosoa, Roberto Schaeffera
⑦	Low Emission Scenarios and Energy Consumption Behaviors for Residential Sector in Korea	The Korean Society of Climate Change Research, Yonsei University	Tae Yong Jung
⑧	Social innovation enablers to unlock a low energy demand future [要旨のみ公開]	University of Wisconsin-Madison	Leila Niamir, Elena Verdolini, Gregory Nemet
⑨	A Comparative Evaluation Of The EDITS Scenarios With Similar Scenarios Produced by Other Major Research Institutions in 2021 & 2022	Stanford University/EMF	John P. Weyant
⑩	2022 年度 EDITS プロジェクト報告書 [一部のみ公開]	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
⑪	1)The ITF passenger transport model: Part of the ITF PASTA framework - Model framework, insights and outputs for the	ITF-OECD	1) Andrea Papu Carrone, Mallory Trouve, Luis Martinez 2) John Pritchard, Luis Martinez

	EDITS 'High-with-Low' Scenario (Passenger), 2) The ITF freight transport model: Part of the ITF PASTA framework - Model framework, insights and outputs for the EDITS 'High-with-Low' Scenario (Freight) 3) The ITF fleet model: Part of the ITF PASTA framework - Model framework, insights and outputs [要旨のみ公開]		3) Matteo Craglia
⑫	Final Version Report Report summarizing the following [要旨のみ公開]: 1) 3D printing and low energy demand in energy-intensive industrial sectors 2) Resource usage spillovers in residential buildings between electricity, natural gas, and water 3) Desirability of LEMD scenarios	CMCC/EIEE	Cristina Cattaneo, Yannik Stuka, Elena Verdolini
⑬	Review of system-wide industry modelling approaches for low energy and materials demand scenarios [要旨のみ公開]	Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna (BOKU)	Dominik Wiedenhofer, Jan Streeck, Stefan Pauliuk

⑭	The Impact of Digital Consumer Innovations: An Analysis of Variance between the Emissions Benefits of Digital Consumer Innovations	Oxford University	Hazel Pettifor, Maureen Agnew, Charlie Wilson, Leila Niamir
⑮	Decarbonizing Global Building Sector- Understanding the potential of net-zero building sector	Central European University on behalf of DBH InnoHub	Dianna Ürge-Vorsatz, Souran Chatterjee, Gergely Molnar
⑯	WP2 Data deliverable Identifying key data gaps in description of Low Energy Demand Pathways [一部のみ公開]	Utrecht University	Oreane Edelenbosch, Hsing-Hsuan Chen
⑰	Is history repeating itself? Lessons from past technology transitions and false starts in the hydrogen economy [要旨のみ公開]	Iscte – University Institute of Lisbon	Nuno Bento
⑱	Acceptability of climate change mitigation pathways A pilot study	University of Groningen	Robert Görsch, Linda Steg
⑲	Annual Report: Energy Demand changes Induced by Technological and Social innovations (EDITS)	International Institute for Applied Systems Analysis (IIASA)	IIASA
⑳	Modeling the direct energy use of internet data communication networks [要旨のみ公開]	University of California, Santa Barbara	Eric Masanet

デジタルトランスフォーメーションによるサーキュラー・シェアリングエコノミーによって誘発され得る低エネルギー需要社会とCO_2排出削減に関するコンピュータモデルを用いた包括的かつ定量的な分析・評価

① 地球環境産業技術研究機構

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。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、COP27 でもパリ協定の 1.5℃目標に基づく取組の実施の重要性を確認された。

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。そして、2021 年 10 月には、2050 年カーボンニュートラル実現目標を前提とした、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、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。更に、2022 年 5 月にはクリーンエネルギー戦略中間整理がなされた。そこでは需要サイドの産業構造転換を含めて議論、整理がなされた。そして、2023 年 2 月には「GX（グリーントランスフォーメーション）実現に向けた基本方針」が閣議決定された。

2℃、1.5℃目標の実現に向けて、エネルギー供給サイドだけではなく、エネルギー需要サイド、そして低エネルギー需要社会実現に向けた社会変化を誘発していく必要がある。しかもそれは、単なる需要の低減ではなく、「経済と環境の好循環」をもたらすような、つまり、ウェルビーイングは向上させつつ需要は低下させる社会の実現を志向する必要がある。RITE では、別途、ALPS 事業において、モデル開発を実施しつつ、本 EDITS 事業の国際モデル比較事業でのシナリオプロトコルに沿い、また、他の研究機関シナリオと調和を図った形で、世界全体で、そしてエネルギー供給サイドと需要サイド、また需要側部門間でも整合性がとれている、定量的なシナリオ作成を行った。

1.1　エネルギー需要側対策の重要性とシナリオ動向

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。そして、IPCC 第 6 次評価報告書[4)]では、新たに需要サイドの対策に特化した章が設けられ現状における論文等のサーベイがなされ、そして、「需要側の対策とエンドユースサービスの新しい提供方法によって、エンドユース部門における世界全体の GHG 排出量をベースラインシナリオに比べて 2050 年までに 40～70% 削減しうる。」、「需要側の緩和対応策は、全ての人々の基本的幸福の向上と整合的である。」（政策決定者向け要約 SPM、C.10）とされた。

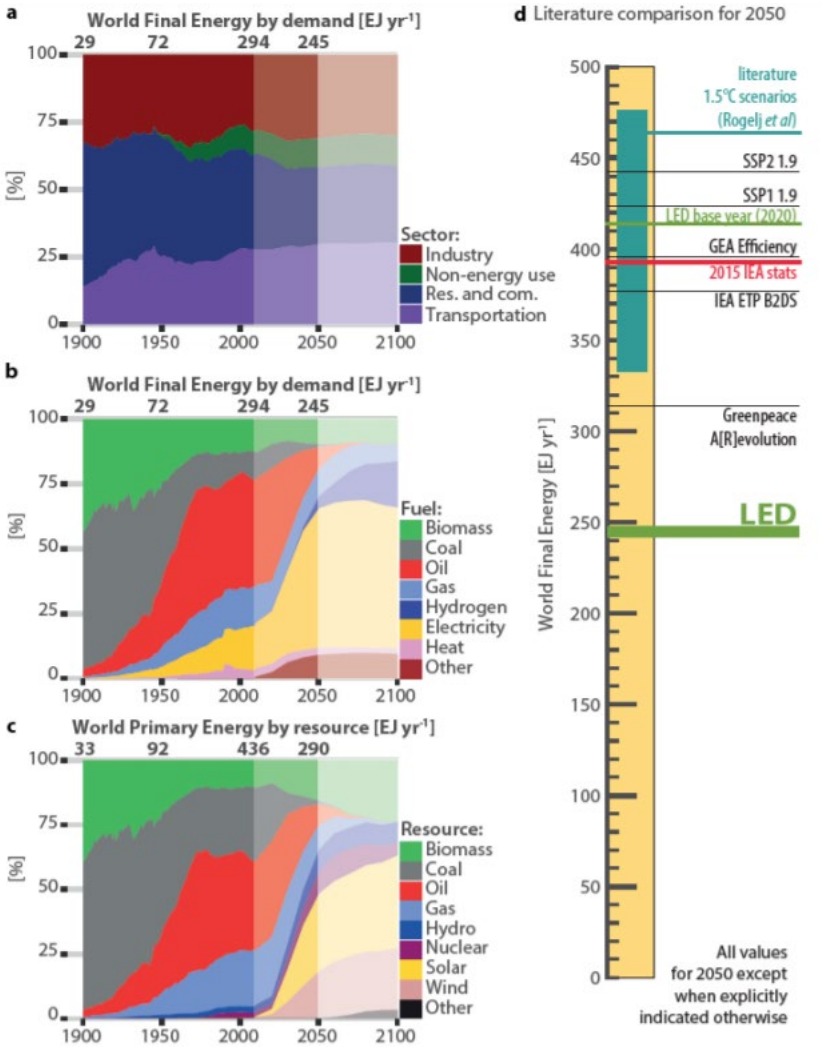
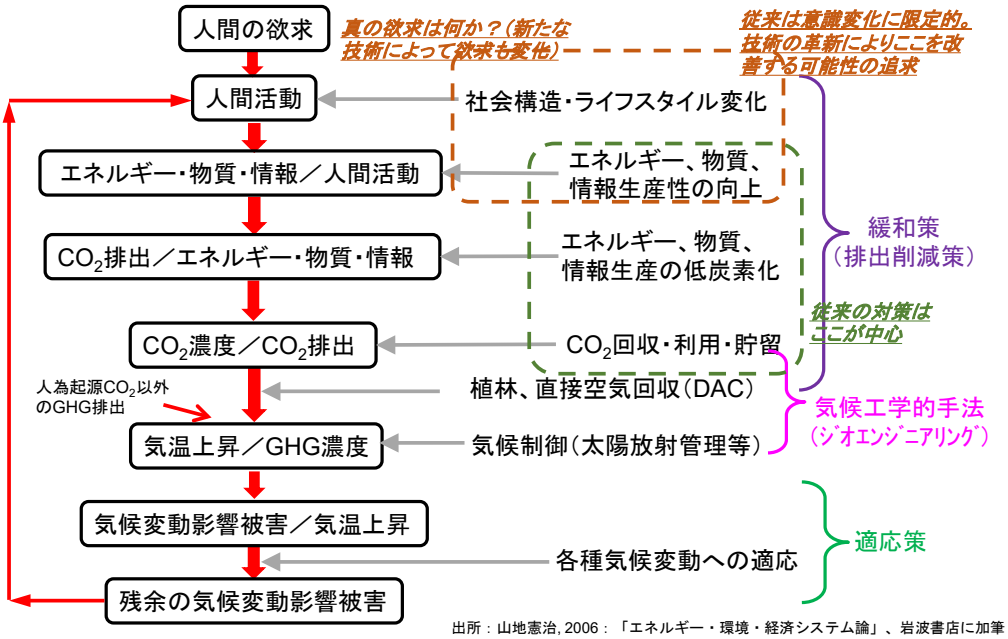


図 1-1 IIASA LED シナリオにおける最終エネルギー消費量 [2)]

図 1-2 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。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。



出所：山地憲治, 2006：「エネルギー・環境・経済システム論」、岩波書店に加筆

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

デジタルトランスフォーメーション(DX)およびその他のイノベーションによって、暗黙的なコストを低減し、比較的安価なコストによって、サーキュラー・シェアリングエコノミーを誘発できる余地が生まれてきている（文献 5)など)。IPCC 第 6 次評価報告書（AR6）[4]でも、文献 5)を含め、各種文献からの各対策におけるエネルギー需要や CO_2 排出量の低減効果に関する報告結果として、図 1-3、図 1-4 のような整理もなされた。推計の幅が大きいものの、エネルギー需要や CO_2 排出量のかなり大きな低減も期待されることが示されている。一方、これらの分析は、各対策の低減率に関する評価であり、部門横断的に整合的かつ定量的なエネルギー低減量や、CO_2 排出低減量が示されているわけではない。また先述のように IPCC AR6 は、「需要側の対策とエンドユースサービスの新しい提供方法によって、エンドユース部門における世界全体の GHG 排出量をベースラインシナリオに比べて 2050 年までに 40～70% 削減しうる。」とした。ただし、各対策をそれぞれ積み上げて評価したものであり、対策コストを含めて、必ずしも整合的かつ定量的なモデルを使って部門横断的に推計したものではない。

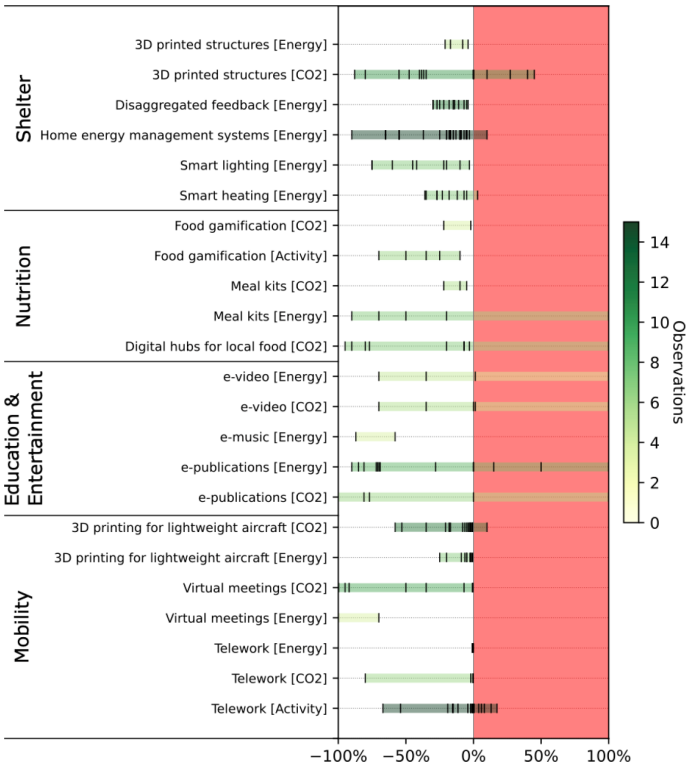


図 1-3 デジタル化によるエネルギー消費・CO_2 排出への影響

（出典：IPCC WG3 AR6[4]）

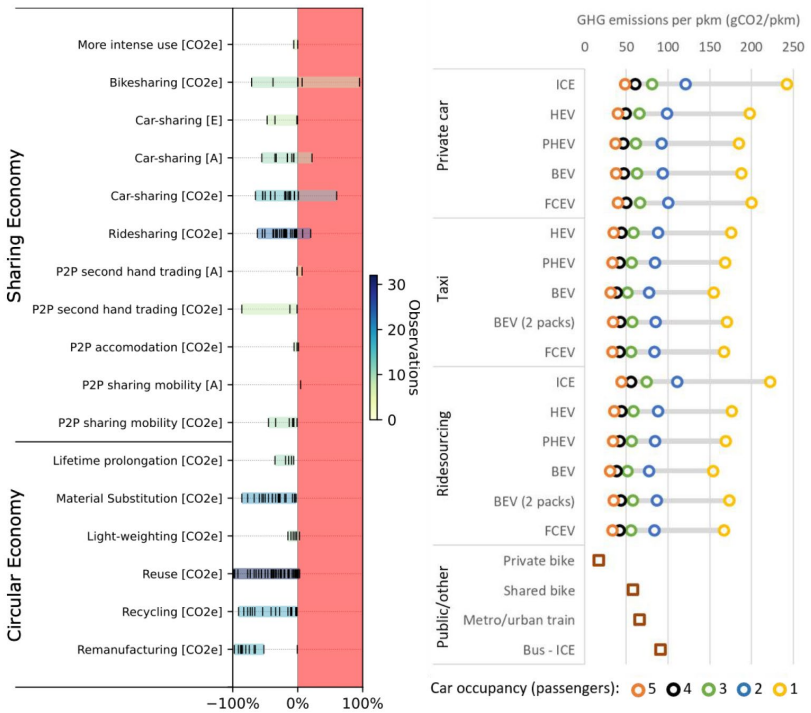


図 1-4 シェアリング・サーキュラーエコノミーによるエネルギー消費・CO_2 排出への影響

（出典：IPCC WG3 AR6[4]）

1.2　DX 等により誘発され得る低エネルギー需要社会のシナリオ分析

複雑なシステムを包括的かつ定量的に分析し、その有用性と課題を明確にしていくことが、DX によって誘発される、サーキュラー・シェアリングエコノミー等の低エネルギー需要社会を社会全体として推進していく上での強力な推進力となると考えられる。本事業で探索し定量的なシナリオとして提示を試みるのは、単なる需要の低減ではなく、「経済と環境の好循環」をもたらすような、つまり、ウェルビーイングは向上させつつ需要は低下させる社会の実現のシナリオである。

RITE では、別途、ALPS 事業において、モデル開発を実施しつつ、本 EDITS 事業の国際モデル比較事業でのシナリオプロトコルに沿い、また、他の研究機関シナリオと調和を図った形で、世界全体で、そしてエネルギー供給サイドと需要サイド、また需要側部門間でも整合性がとれている、定量的なシナリオ作成を行った。第 2 章でそのシナリオについて記載した。

なお、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。更に、時間や所得のバジェットがあり、そのバジェットにおける他用途での利用といったリバウンドも想定される。それら複雑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、引き続き、多くの研究課題が残っている。

第2章　需要側変化に関する定量的な分析のための各種想定シナリオ

2.1　定性的なシナリオ

本 EDITS（Energy Demand changes Induced by Technological and Social innovations）事業においては、ナラティブ WG において、図 2-1 のようなドライバーを考慮した定性的なシナリオ”high wellbeing with low resource use (High-with-Low)”シナリオが提示された [6]。RITE では、本年度、これを基に ALPS（ALternative Pathways toward Sustainable development and climate stabilization）事業において定量的なシナリオ策定を行って、そのシナリオを国際モデル比較プロジェクトである EDITS に提供した。

デジタル化の進展と新結合によるイノベーション、そして適切な生活水準（DLS）が融合した世界観であり、well-being を高めながら、低需要（エネルギーおよび各種物質や製品等）を実現し得るとするシナリオである。要素間の関係性については、図 2-2 に示す。

これまでの統合評価モデル（IAM）分析では、最終エネルギー消費量を人口、GDP のシナリオから外生的に与え、弾性値等を使って気候変動対策下での最終エネルギー消費量を推計するといった手法をとることが多い。しかし、産業などの需要はあくまで well-being を高める消費行動による結果としての需要である。エネルギー需要は、あくまで製品・サービスを得るための派生的需要である。製品・サービスを得る消費行動の変化に焦点を当て、結果としての素材製品やエネルギー需要の低減を推計し、その上で、全体としてのエネルギー需給、そして、結果としての CO_2 排出量を推計していく手法が新規性の高いところとなっている。それを通して、需要サイドの対策の効果の見える化を図り、「経済と環境の好循環」実現に向けた社会変化の誘因としていく。

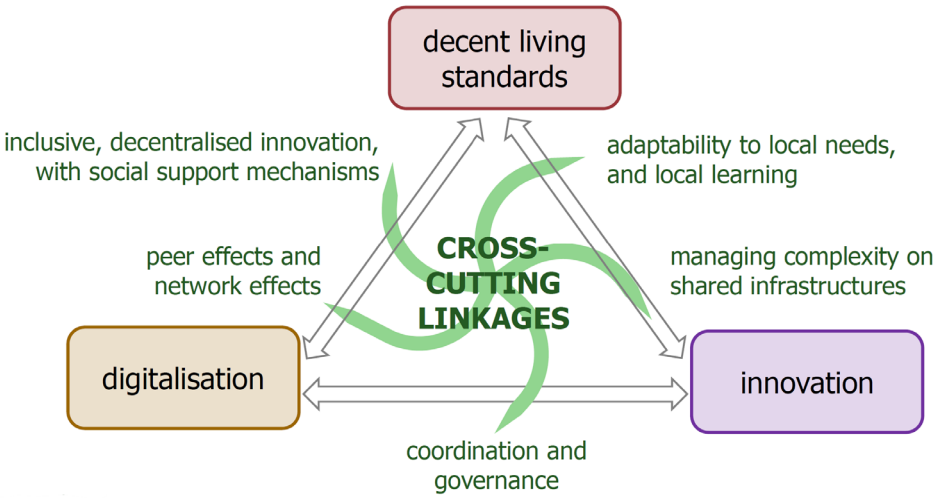


図 2-1　定性的シナリオ’High-with-Low’の想定ドライバー
（出典：EDITS WG3 Narratives group シナリオ [6]）

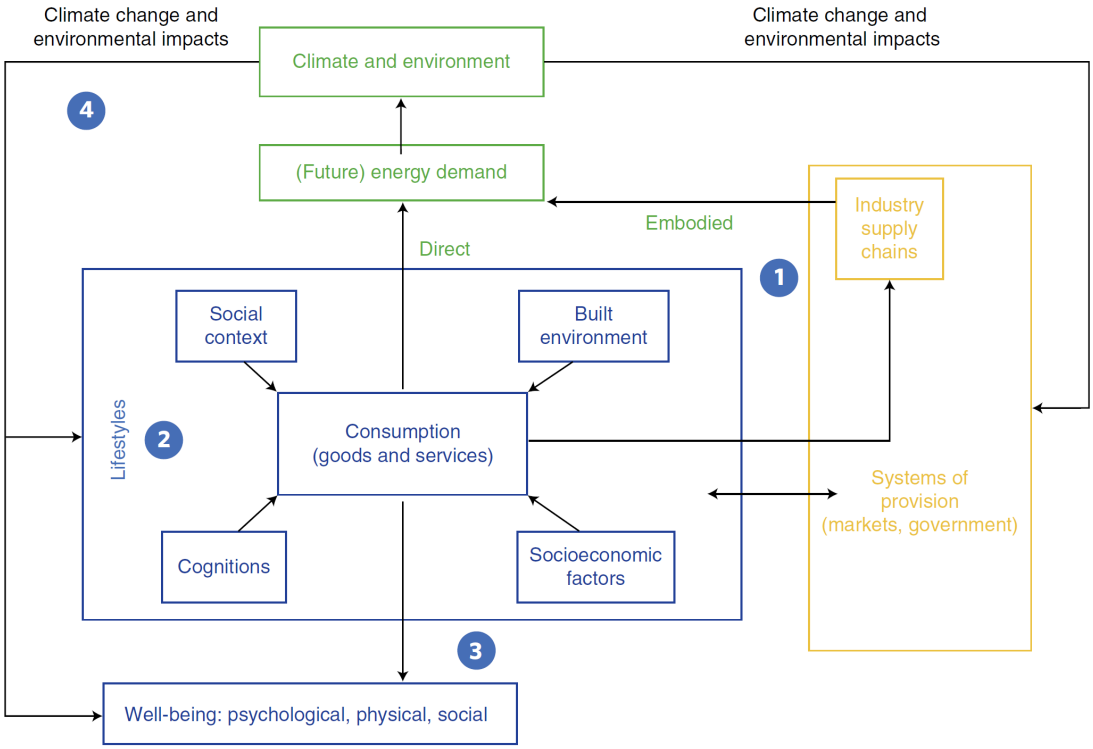


図 2-2 定性的シナリオ’High-with-Low’の要素間の関係

（出典：EDITS WG3 Narratives group シナリオ [6]）

2.2 定量的な分析のためのシナリオ想定

世界エネルギー・温暖化対策評価モデル DNE21+を用いて、DX を中心にして誘発されるサーキュラーエコノミー、シェアリングエコノミーによる、低エネルギー需要社会の実現、そして、GHG 排出量の低減効果を定量的に推計した。推計には現時点では定量的なデータ入手の困難性もあり、波及効果について一部しか考慮できていないことに注意が必要である。また、モデル前提条件の想定についても、不確実性が大きく、より良いデータの入手、反映の課題が残っている。DNE21+モデルは、鉄鋼、セメント、化学製品など、CO_2 排出原単位の高い製品を積み上げ評価しているため、サーキュラーエコノミー、シェアリングエコノミー等による基礎素材製品の低下、それに伴うエネルギー消費の低下等を整合的に分析可能である。

図 2-1 のような定性的なシナリオドライバーを基に、定量的なシナリオ想定を行った。表 2-1、表 2-2 に分析を行った、DX によるサーキュラーエコノミー（CE）誘発のシナリオ想定を示す（以降、本報告書では、シェアリングエコノミーもサーキュラーエコノミーに内包されるものとして、CE と記載する）。また、表 2-3 には、分析を行ったシナリオ名と、各シナリオの想定内容を示す。排出シナリオとしては、特段の排出シナリオを想定しないベースラインと、2℃、>66%確率の B2DS シナリオを想定した。B2DS では、別途、日本を含む主要先進国それぞれについては 2050 年 GHG のカーボンニュートラルを想定した。

表 2-1　DX によるサーキュラーエコノミー（CE）誘発のシナリオ想定

DX による CE 誘発等	エネルギー消費への直接的な影響	エネルギー消費への間接的な影響	DNE21+モデル分析における想定（暫定試算）	参考文献および備考
1) 完全自動運転車等の実現により誘発されるライドシェア、カーシェアリング（2030 年時点までは想定せず）	- ライドシェアによる乗用車用エネルギー消費量の低減	- カーシェアリングに伴う乗用車台数の低下に伴う、鉄鋼、プラスティック、ゴム、ガラス、コンクリート等の低減 - 製品、素材の国際貨物輸送の低減⇒項目 8)	- 鉄鋼製品生産量：▲4%（車両＋立体駐車場。道路建設含まず） - プラスティック製品： ▲1% - タイヤ製品：▲28%（乗用車向け比）（エネルギー消費量低減換算値をモデルで想定） - ガラス製品：▲28%（乗用車向け比）（エネルギー消費量低減換算値をモデルで想定） - セメント製品：▲1%（立体駐車場のみ。道路建設含まず）	ライドシェア、カーシェアリングについて、一台当たり乗車人数、一台当たり走行距離等を想定し、乗用車生産台数、保有台数の低減を DNE21+モデルで評価（Akimoto et al.　(2022) Technol. Forecast. Soc. Change を拡張評価）。 - 台数低減に伴う各種製品の低減は、鉄鋼新聞(2016)、Chester et al.(2010)、石油化学教会(2018)、国立環境研究所(2003)、日本自動車タイヤ協会(2022)、機械システム振興協会(2007)に基づき評価。
2) バーチャルミーティング、テレワーク	- 移動の低減に伴う運輸部門のエネルギー消費量の低減	- *長期的に建築物の稼働率上昇、必要な空間面積の低減により、鉄鋼、コンクリート等の低減の可能性有*【今回のモデル分析では未考慮】	- 旅客需要：▲10%	- Tao et al. (2021) Nature Communications
3) E-publication 等による紙の代替	- 紙の生産のためのエネルギー消費量の低減	- *紙媒体の配送等の貨物需要低減の可能性有*【今回のモデル分析では未考慮】	- 紙パ生産量：▲20%	- IPCC WG3 AR6 (2022) Fig. 5.12 の推計幅を参考にしつつ想定
4) E-コマースや他の DX によるアパレルのリサイクル・シェア化の促進	- アパレル製造のエネルギー消費の低減	- *ショッピングセンター等、小売店舗の低減と、それに伴うエネルギー消費、また建築物建設の低減により、鉄鋼、コンクリート等の低減の可能性有*【今回のモデル分析では未考慮】	- アパレル生産量：▲20%（エネルギー消費量低減換算値をモデルで想定）	- 木谷佳楠 他(2022)エネルギーシステム・経済・環境コンファレンス

赤字： 家庭部門関連、 緑字： 業務部門関連、 青字: 輸送部門関連、 紫字： 産業部門関連、茶字：非 CO_2 GHG 等

表 2-2 DX によるサーキュラーエコノミー（CE）誘発のシナリオ想定（続き）

DX による CE 誘発等	エネルギー消費への直接的な影響	エネルギー消費への間接的な影響	DNE21+モデル分析における想定（暫定試算）	参考文献および備考
5) 都市開発、設計等の進展による建築物の高寿命化	- 建築物の高寿命化による、セメント、鉄鋼製品の低減に伴うエネルギー消費量の低減		- 建築物の高寿命化：+40%、それに伴うセメント：▲3%、鉄鋼製品需要の低減：▲3%	- Pauliuk et al.(2021)の住宅用セメント、鉄鋼製品のフローおよびストックのデータに基づき、2100 年までのシナリオを作成し、建築物の寿命を+40%とした場合の効果を算定。
6) 需要予測の向上等による食品廃棄の低減	- 必要食品生産量の低減等に伴う、窒素肥料、プラスティック製品等の生産に伴うエネルギー消費量の低減 - 小売店舗等のエネルギー消費量の低減 - 必要食品生産量の低減等に伴う、メタン、一酸化窒素排出量の低減	- 農畜産物、食品等の低減に伴う国際貨物輸送の低減 ⇒ 項目 8) - *食品販売量の低減に伴う、小売店舗の低減に伴う鉄鋼、コンクリート製品等の低減の可能性* 【今回のモデル分析では未考慮】 - *他用途への利用可能な土地面積の増大に伴う植林等による CO2 固定可能性* 【今回のモデル分析では未考慮】	- 石油化学製品（窒素肥料含む）の低減：▲1% - プラスティック製品：▲1% - 紙パ製品：▲0.5% - 輸送サービス需要：▲1% 他 (以上、産業連関表より算定) - メタン、一酸化窒素排出低減：▲493 MtCO2eq/yr in 2050	需要予測等、情報技術の導入費用を考慮の上、食品廃棄低減による関連部門への波及効果を GTAP10 の I-O に基づき算定（林礼美他(2022) エネルギーシステム・経済・環境コンファレンスを拡張評価）。 - 小売・卸・食品加工：POS システムを用いた需要予測により食品廃棄率低減すると想定 - 家庭：食品ロスダイアリーアプリの使用により食品廃棄が低減。例：導入強化により、成り行きケース比約 50%減 - ReFED(2021) Explore solutions to food waste - 京都経済短期大学他(2020) 食品ロス削減による経済便益に関する調査・分析
7) 3D プリンティングの適用による素材の低減	- アルミニウム、鉄鋼製品等の低減 - 製造段階による電力消費量の低減	- 航空機の軽量化に伴う運航時のエネルギー消費量の低減 - *自動車等の軽量化に伴うエネルギー消費量の低減* 【今回のモデル分析では未考慮】	- アルミニウム製品：▲1% - 鉄鋼製品：▲0.02% - 直接的電力消費量：▲1% - 航空機の運航時のエネルギー消費量：▲10%	Verhoef et al.(2018)に基づく。2050 年に AM による生産比率が 100%となり下記等の効果が見込める。 - メタル原料が 90%削減 - 加工での電力消費量が 35%削減 - 機体軽量化により燃料重量が 16.7%削減
8) 基礎素材やその他製品需要の低減に伴う国際海運需要の低減	- 国際海運需要の低減によるエネルギー消費量の低減		- 国際海運需要：▲1%	- 1)、6)、7)で見込まれた製品需要の低減に伴う国際海運需要の低減を想定。

赤字： 家庭部門関連、 緑字： 業務部門関連、 青字: 輸送部門関連、 紫字： 産業部門関連、茶字：非 CO_2 GHG 等

表 2-3 モデル分析のためのシナリオ想定

	排出削減経路	主にデジタル化によるエネルギー需要低減						電力需要のフレキシビリティ(EV, HP, CGS)	小規模技術(PV、風力、EV等)のより急速なコスト低減
		運輸 1)	家庭 2, 3, 4)	建築物 5)	農業・食品 6)	産業 7)	派生効果 8)		
BL-Std	Baseline (特段の気候変動緩和政策を想定せず。炭素価格0)	—	—	—	—	—	—	—	—
BL-Mobil		○							
BL-Resid			○						
BL-Build				○					
BL-Food					○				
BL-Ind						○			
BL-All_CE		○	○	○	○	○	○		
BL-All_CE+FL		○	○	○	○	○	○	○	
BL-All_CE+FL+GR		○	○	○	○	○	○	○	○
B2DS-Std	B2DS 2 °Cを十分に下回る排出に抑制(かつ2030年の各国NDCsを想定、主要先進国:2050年GHGでのCN)	—	—	—	—	—	—	—	—
B2DS-Mobil		○							
B2DS-Resid			○						
B2DS-Build				○					
B2DS-Food					○				
B2DS-Ind						○			
B2DS-All_CE		○	○	○	○	○	○		
B2DS-All_CE+FL		○	○	○	○	○	○	○	
B2DS-All_CE+FL+GR		○	○	○	○	○	○	○	○

注1) 今回の分析では、IPCC等で用いられている共有社会経済パス(SSP)は、中位的なSSP2ベースで分析
注2) 本来、DXによる電力消費量の増大等のリバウンド効果も考えられるが、CO2限界削減費用低下に伴うリバウンド効果以外のリバウンド効果は今回考慮していない

需要側のデジタル化の進展、イノベーションとして、CE 関連だけではなく、変動性再生可能エネルギーの利用増大に資する、電力需要側の柔軟性の提供の可能性についても考慮した。具体的には、DNE21+の電力需要曲線において、BEV や PHEV、ヒートポンプ給湯器、コジェネレーションシステムが、特に太陽光の日中の供給力の需要調整を、標準のシナリオよりも、柔軟に提供できると想定した(”FL”シナリオ)。系統統合費用については、BEV、PHEV の逆潮流の発生によって、系統側での蓄電池低減を伴うことも想定し、図 2-3 で示すように系統統合費用の低減が可能と想定した。

また、需要側技術は、granular technologies と呼ばれるような規模の小さい技術が多い。これら技術は、サイクルが早いことがあって、一般に技術習熟率が高い傾向が観測される。DNE21+では、太陽光発電や風力発電、EV 用バッテリーなど、標準シナリオでも大きなコスト低減を見込んでいる。しかし、これら比較的規模の小さい技術の技術習熟率が一層高くなるシナリオ(”GR”シナリオ)も想定した。ただし、このシナリオはあくまで外生的な想定であり、参考として他シナリオの結果と比較するべきものという位置づけであることに注意されたい。具体的な想定は、太陽光発電コスト:図 2-4、風力発電コスト:図 2-5、EV の車両コスト:表 2-4、HP 給湯器のコスト:表 2-5、コジェネレーションシステムのコスト:表 2-6 として示している。

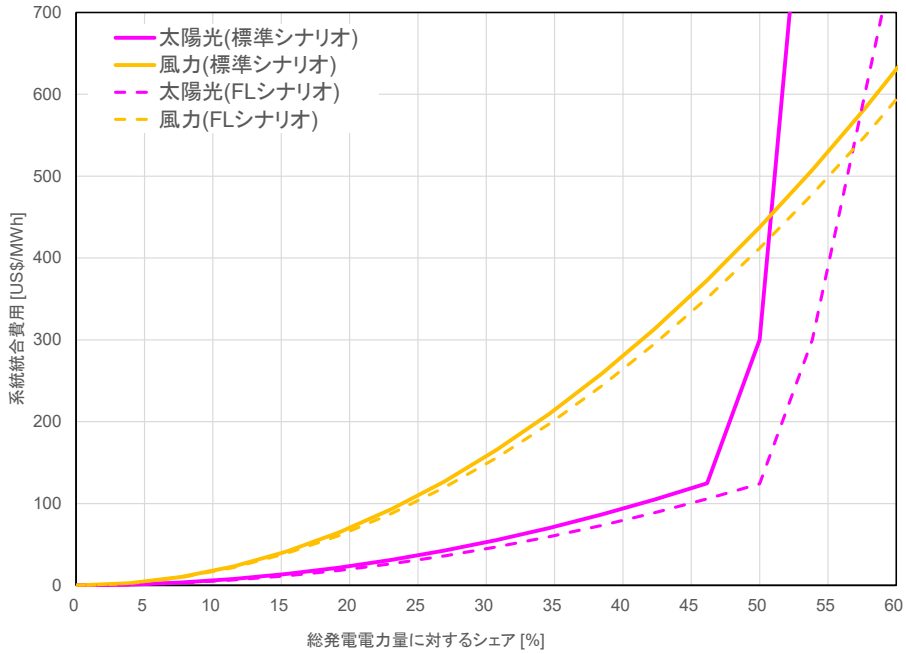


図 2-3 系統統合費用の想定（日本、2050 年、標準シナリオと FL シナリオ）

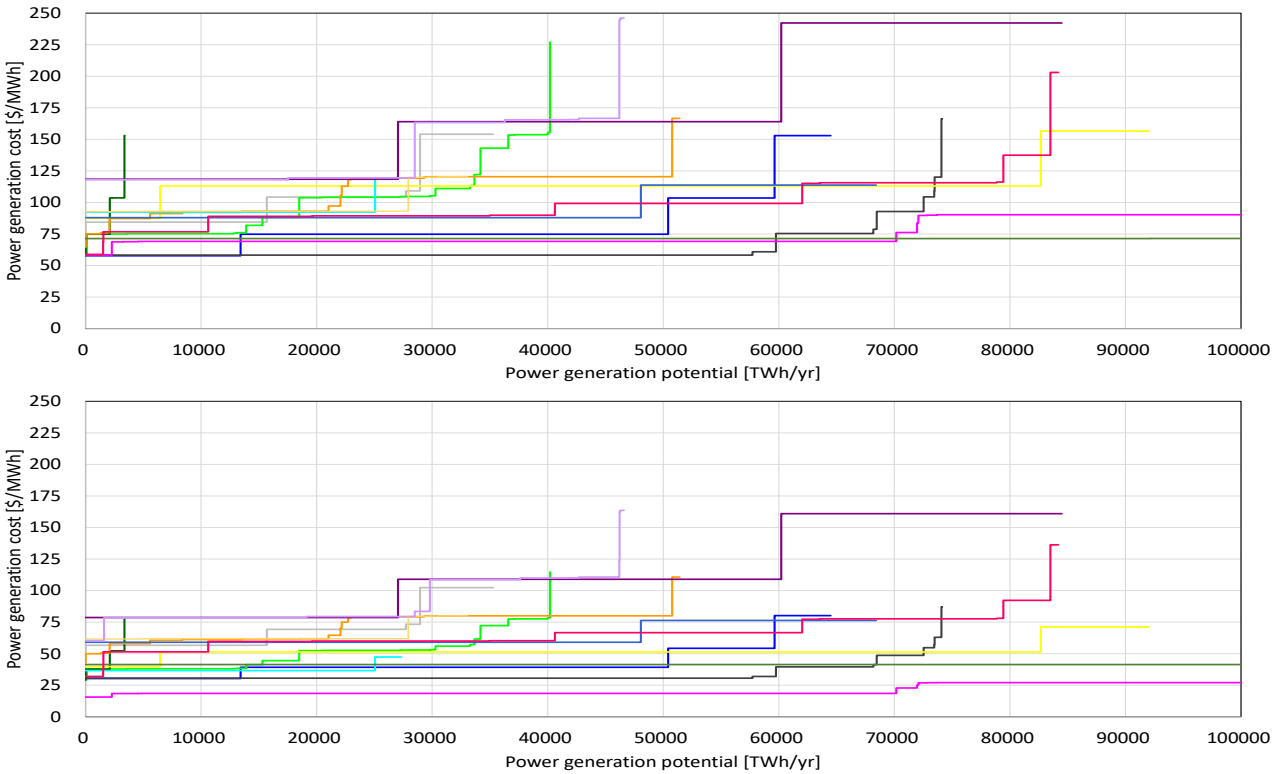


図 2-4 太陽光発電コストの想定（上図：標準、下図：GR シナリオ）

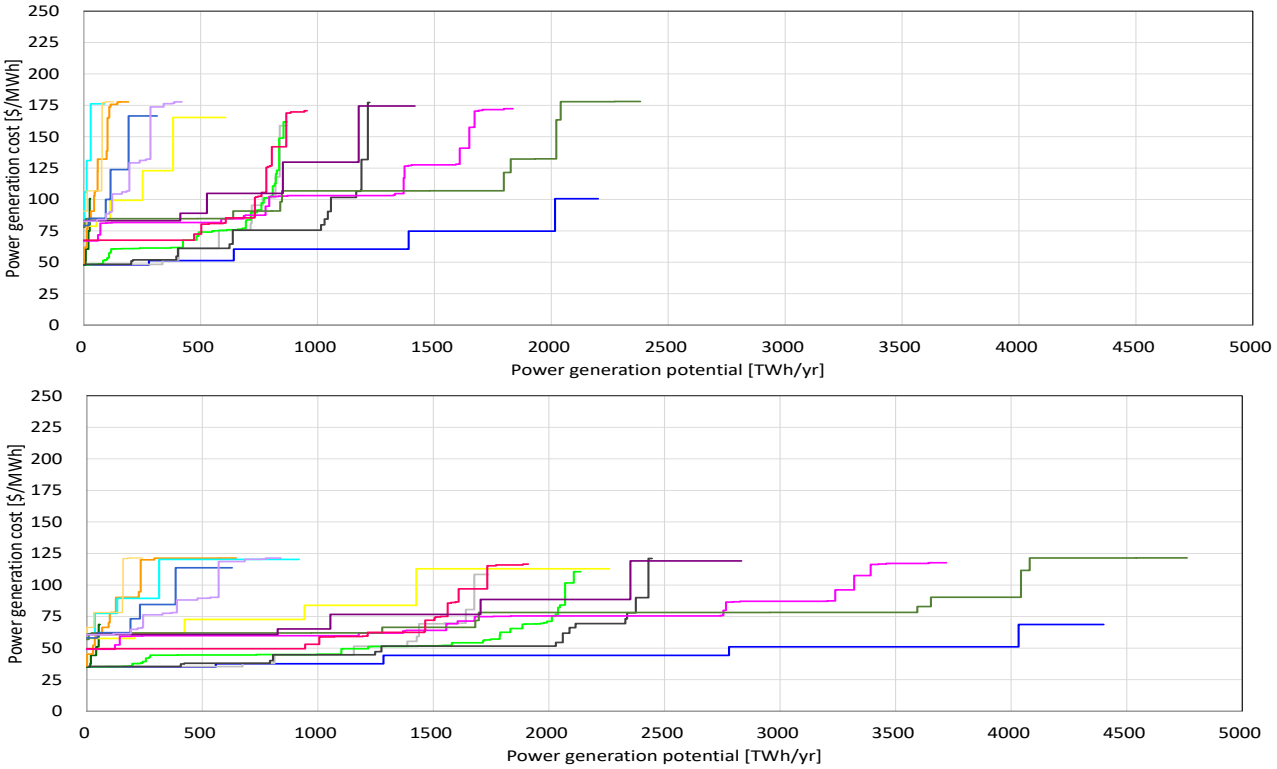


図 2-5 風力発電コストの想定（上図：標準、下図：GR シナリオ）

表 2-4 EV（小型乗用車）の車両コストの想定（標準シナリオと GR シナリオ）

		2015	2020	2030	2050
在来型内燃自動車	標準	170	170	180	185
	GR		170	180	185
ハイブリッド車（ガソリン）	標準	210	209	202	201
	GR		208	201	201
プラグインハイブリッド車（ガソリン）	標準	270	248	219	210
	GR		244	210	205
純電気自動車（BEV）	標準	311	305	265	225
	GR		285	210	205
燃料電池自動車（FCEV）	標準	598	514	388	244
	GR		412	244	205

単位：万円/台

注）バッテリーコスト：標準シナリオ 2030 年 2 万円/kWh、2050 年 1 万円/kWh 相当、GR シナリオ 2030 年 1 万円/kWh、2050 年 5 千円/kWh 相当。

表 2-5　HP 給湯器のコストの想定（標準シナリオと GR シナリオ）

	2020	2030	2050	2100
標準	21	21	21	21
GR	21	16	11	11

単位：万円/kW

表 2-6　コジェネレーションシステムのコストの想定（標準シナリオと GR シナリオ）

		2020	2030	2050	2100
産業	標準	15	15	15	15
	GR	15	14	12	12
業務 1	標準	23	23	23	23
	GR	23	21	18	18
業務 2	標準	30	30	30	30
	GR	30	28	24	24
家庭	標準	94	54	43	43
	GR	94	50	34	34

単位：万円/kW

2.3　需要側変化に関するシナリオ分析結果

まず、特段の気候変動緩和政策を想定しない、Baseline シナリオの結果を示す。図 2-6、図 2-7 に、CE 進展を想定しない標準シナリオ（Std）からの世界の最終エネルギー消費量の低減と、GHG 排出量の低減をそれぞれ示す。かなり限定された波及効果のみを考慮した分析段階ではあるものの、想定したサーキュラーエコノミー・シェアリングエコノミー実現によって部門横断的に大きな省エネ効果が期待できることが示されている。また、GHG の排出低減効果も大きいことが推計される。完全自動運転車等の実現によって誘発されるカーシェアリング、ライドシェアによる低エネルギー需要への寄与は、今回想定した DX の効果としては、産業部門への波及を含めて大きいが、それ以外にもバーチャルミーティングなどの効果等も大きい効果があることを示している。食品ロスの低減は、特に非 CO_2 GHG の削減を大きく促す可能性を示している。

同じく、B2DS シナリオについて、図 2-8、図 2-9 に、CE 進展を想定しない標準シナリオ（Std）からの世界の最終エネルギー消費量の低減と、GHG 排出量の低減をそれぞれ示す。かなり限定された CE の事例および波及効果のみを考慮しただけでも、2050 年では、現在の世界の最終エネルギー消費量全体の 6%程度、また、2℃目標下で経済合理的と推計される省エネ量の半分程度もの省エネが、サーキュラーエコノミー・シェアリングエコノミーによって更に追加できる可能性が示唆される。排出削減目標が決まっている条件では、想定したサーキュラーエコノミー・シェアリングエコノミー対策は

相対的に費用が安価なため、限界的な費用の対策と評価される、CCS 付きバイオエネルギー（BECCS）や大気中 CO_2 直接回収貯留（DACCS）といった二酸化炭素除去（CDR）技術への寄与を低減し得る。なお、最終エネルギー消費量の低減効果は大きいが、CO_2 削減効果は、エネルギー供給側の CO_2 原単位低減も伴っているため、エネルギー消費量ほど、大きくは算定されない。ただし、後述のように、費用低減効果は大きい。

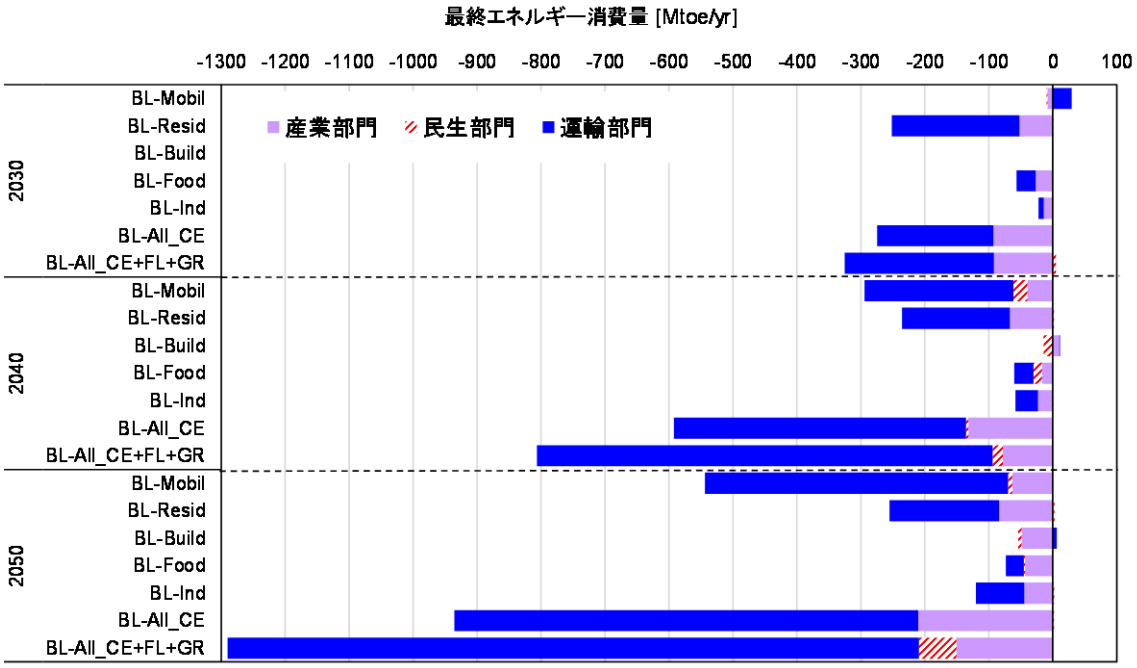


図 2-6　世界エネルギー消費量（ベースラインシナリオ、CE 想定時の変化）

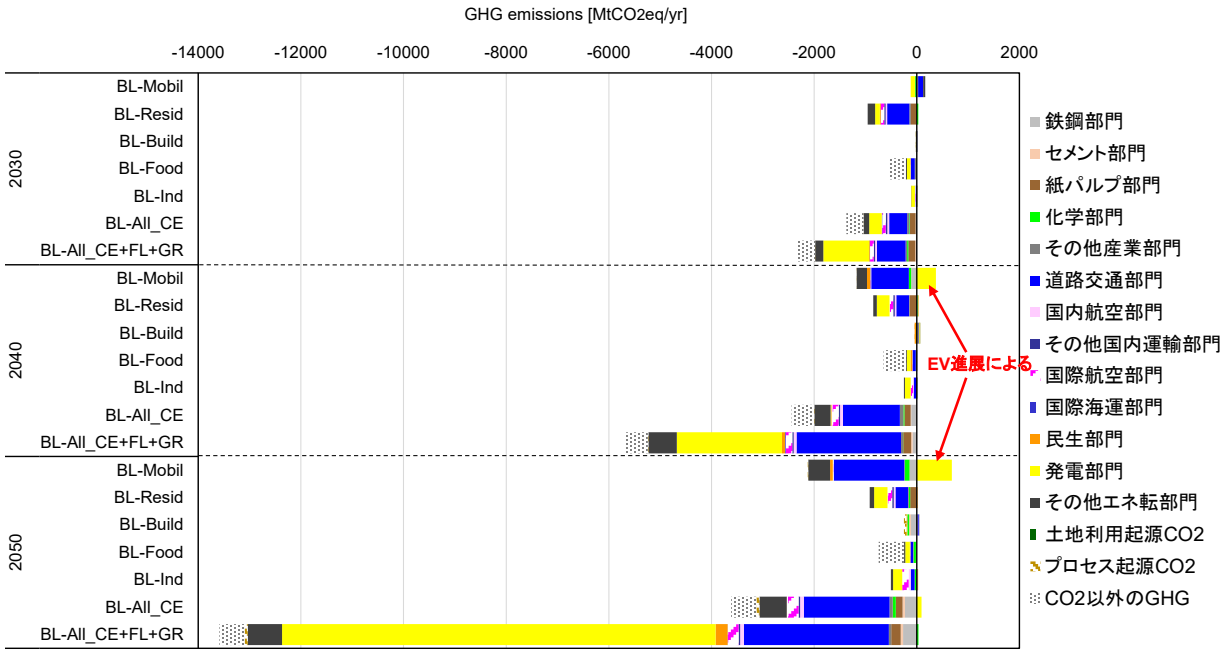
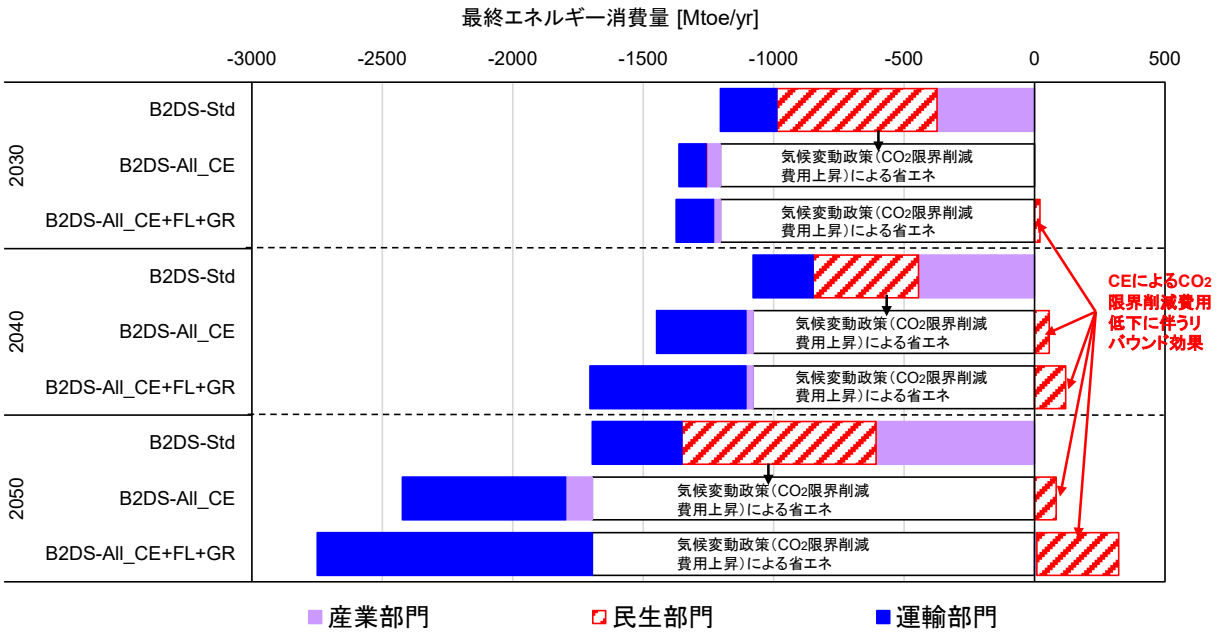
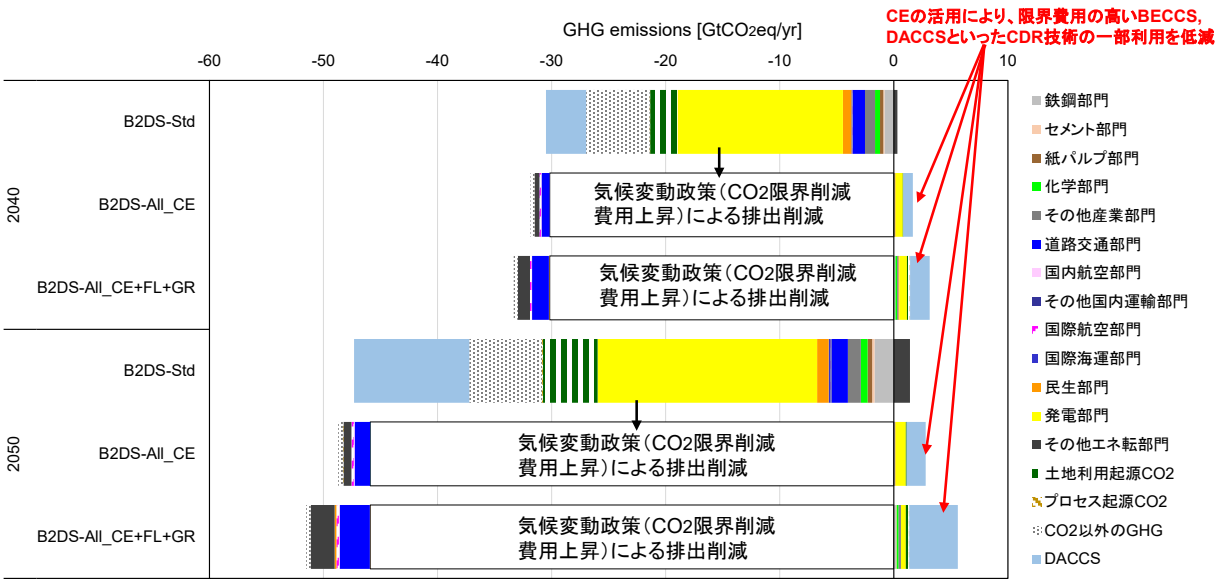


図 2-7　世界の GHG 削減効果（ベースラインシナリオ、CE 想定時の変化）



参考）2019年の世界の最終エネルギー消費量実績値：10 Gtoe/yr、2050年のベースラインの最終エネルギー消費量推計値：14 Gtoe/yr

図 2-8 世界エネルギー消費量（B2DS（2℃制約シナリオ）下、CE想定時の変化）



参考）2019年の世界のGHG排出量実績値：59 GtCO2eq./yr、2050年のベースラインの排出量推計値：73 GtCO2eq/yr

図 2-9 世界の GHG 削減効果（B2DS（2℃制約シナリオ）下、CE想定時の変化）

図 2-10 には、世界地域別の一人当たり最終エネルギー消費量を示す。先進国では、特に需要側で必要以上に多くのエネルギーが消費されており、’High-with-Low’シナリオは、主に先進国の低エネルギー需要の実現を誘発し、一人当たりエネルギー消費の国際的な格差を縮小させる。

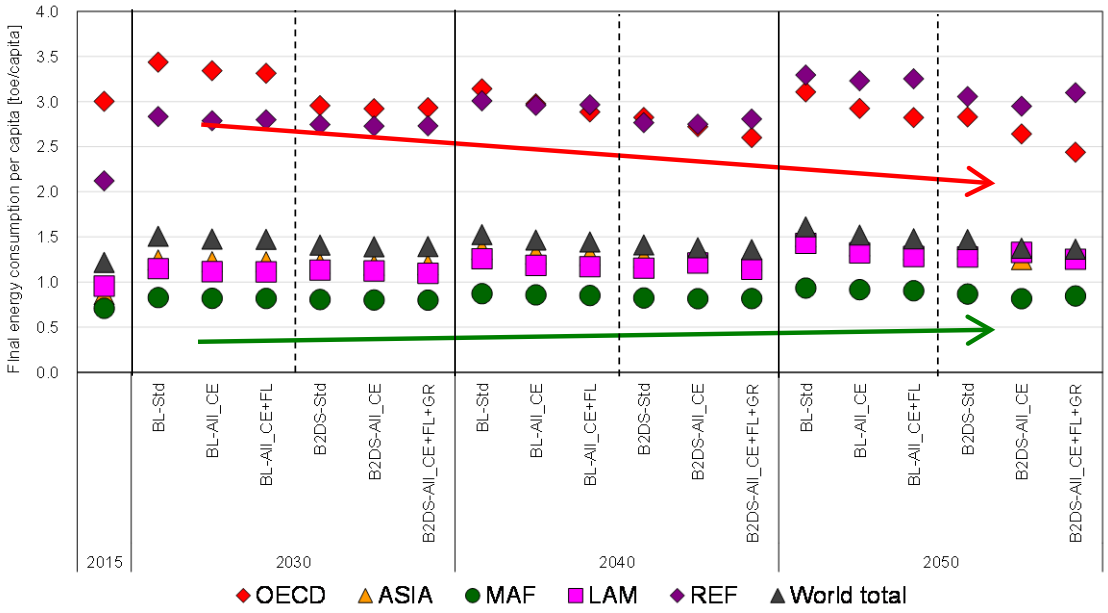


図 2-10 世界地域別の一人当たり最終エネルギー消費量

表 2-7 には、CE シナリオ下におけるエネルギーシステム総コストの Std シナリオ比での低減を、また、表 2-8 には、B2DS 時の CO_2 限界削減費用を示す。DX に誘因された CE の推進により、エネルギーシステムコストの大きな低下が推計される。特に完全自動運転車等によるライドシェア、カーシェアによって社会全体としての大きなコスト低減効果が期待できるが、テレワークなどの家庭部門の変化、食品ロス低減なども、エネルギーシステムコストの低減に比較的大きな効果が期待できる。

また、表 2-8 で確認できるように、2℃目標等の長期目標の実現においては、CO_2 限界削減費用の低下（2～3 割程度）が期待できる。

表 2-7 エネルギーシステム総コストの低減：CE 想定時（単位：Billion USD/yr）

	Scenarios	Mobil	Resid	Build	Food	Ind	All_CE	All_CE +FL	All_CE +FL+GR
2030-2040 年の間の年平均値	Baseline	▲547	▲339	▲1	▲57	▲4	▲894	▲894	▲963
	B2DS	▲556	▲352	▲0	▲64	▲5	▲926	▲928	▲1038
2040-2050 年の間の年平均値	Baseline	▲1601	▲459	▲1	▲74	▲7	▲1971	▲1971	▲2085
	B2DS	▲1635	▲477	▲6	▲90	▲14	▲2037	▲2038	▲2266

※ Baseline、B2DS のそれぞれの排出シナリオの標準ケースからの CE ケースによるコスト低減分

表 2-8 B2DS 時の CO_2 限界削減費用（単位：USD/tCO_2eq）

	B2DS-Std	B2DS_All-CE	B2DS_All-CE+FL	B2DS_All-CE+FL+GR
2040 年	68–310	57–238	57–240	50–195
2050 年	146–739	123–524	122–522	60–364

※ 限界削減費用の幅は国による差異

最後に今回分析の BL-Std シナリオおよび B2DS_All-CE+FL+GR シナリオを、IEA WEO シナリオ [7]と比較したグラフを図 2-11 に示す。グラフには、LED シナリオ [2]、そして更に、Millward-Hopkins らによる、必要十分なエネルギー消費量推計のシナリオ [8]を併せて記載している。デジタル化によって誘発され得る、サーキュラーエコノミー・シェアリングエコノミー等によって、大きなエネルギー低減効果は算定されたものの、LED シナリオ等とは相当大きなギャップがある。また、同じく 2℃、>66%確率の B2DS_All-CE+FL+GR と IEA SDS を比較しても、相当大きなギャップがある。IPCC AR6 の 2℃シナリオ相当（C3 カテゴリー）と比較すると、DNE21+のシナリオは、中位的なシナリオとなっている。一方、IEA SDS や LED は、かなり低い最終エネルギー消費量の推計をしている。

今回の分析では、一部の DX の期待効果のみをモデル化していること、また、定量的なデータが限られることから、波及効果についても一部のみ評価したため、今後の更なる分析によって、より低最終エネルギー消費量の推計となることが見込まれるものの、それでも、IEA SDS や LED とのギャップは大きいことに留意が必要である。引き続き、より低エネルギー需要を実現する可能性を検討、分析を強化するとともに、IEA SDS、LED シナリオ等とのギャップの理解促進が重要と考えられる。

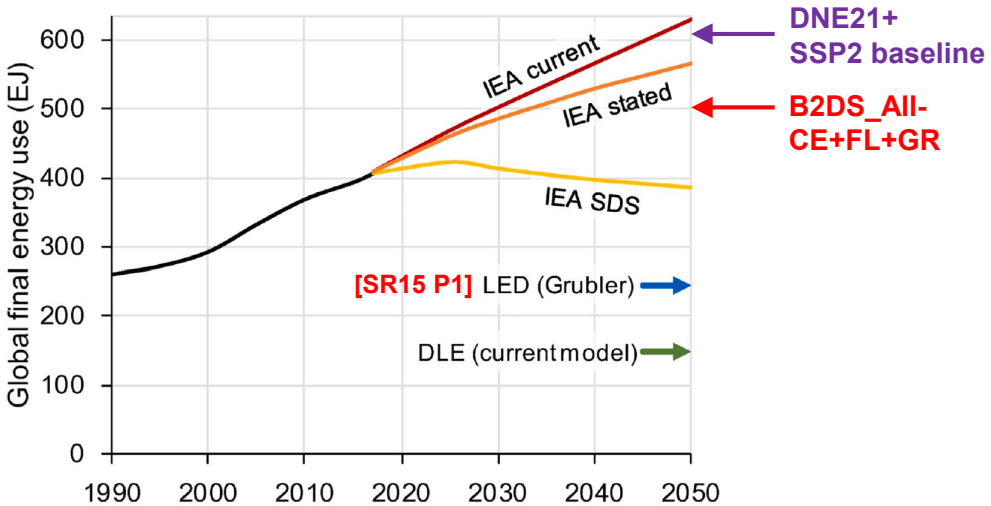


図 2-11 世界エネルギー消費量の見通し：他シナリオとの比較

（出典：文献 [8]グラフに追記）

① 地球環境産業技術研究機構

第3章　まとめと今後の課題

本年度は、ナラティブグループが提示した定性的なシナリオ” high wellbeing with low resource use (High-with-Low)”のコンセプトに沿って、地域・国、部門横断で整合的かつ定量的なシナリオとして世界エネルギー・温暖化対策評価モデル DNE21+において、モデル化を行い、一次試算を行った。本年度の分析では、定量的な推計の困難さから、一部の DX によって誘発され得るシェアリングエコノミー、サーキュラーエコノミーについてのみ、モデル化して分析・評価を行った。また、その波及効果についても定量的な推計の困難さから、限定的な波及効果のみ考慮した。それにも関わらず、相応のエネルギー低減効果、GHG 排出削減効果が推計された。また、エネルギーシステムコストの低減や、B2DS シナリオ（2℃未満、>66%確率）では CO_2 限界削減費用の低下が推計された。これは、まさに「経済と環境の好循環」もしくは「high wellbeing with low resource use」の可能性を示すシナリオと言える。

しかしながら、IPCC SR1.5 で取り上げられた Low Energy Demand (LED)シナリオにおける最終エネルギー消費量の推計は、本分析の推計値を大きく下回るものであり、引き続き、様々な DX によって誘発され得る各種対策、更に派生的に誘発され得るシェアリングエコノミー、サーキュラーエコノミー等の社会変化を定量的にモデル化し、定量的なシナリオ評価を実施してく必要がある。一方で LED シナリオとギャップが生じる理由の理解を深めていくことも重要と考えられる。定量的かつ包括的な分析を一層進めること、他方でそれでもなおギャップが存在するのであれば、そのギャップの理解を深めることが、次期 IPCC 報告書等の評価等で重要になると考えられる。また、エネルギー低減側の評価だけではなく、リバウンド効果も含めた分析も進め、より一層の包括的な評価を行っていくことが重要である。

参考文献

1) IPCC, Special Report on Global Warming of 1.5 C (2018)
2) A. Grubler et al. A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. Nat. Energy, 3(6), 515–527 (2018)
3) C. Wilson et al., Granular technologies to accelerate decarbonization. Science, 368(6486), 36–39 (2020)
4) IPCC WG3, 第 6 次評価報告書 (2022)
5) C. Wilson, L. Kerr, F. Sprei, E. Vrain, M. Wilson, Potential Climate Benefits of Digital Consumer Innovations. Annu. Rev. Environ. Resour., 45(1) (2020)
6) EDITS WG3 Narratives group (Arnulf Grubler, Greg Nemet, Shonali Pachauri, Charlie Wilson), The 'High-with-Low' Scenario Narrative (2022)
7) IEA World Energy Outlook 2019 (2019)
8) J. Millward-Hopkins et al., Providing decent living with minimum energy: A global scenario, Global Environmental Change, 65, 102168 (2020)

Energy Technologies Area
Lawrence Berkeley National Laboratory

Assessment of Market Adoption and Cost Data, and Supporting Policies for Technological Innovations to Reduce Energy Demand

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Abstract

Building on earlier reports that focused on reviewing the energy and emissions impacts of specific technological and social demand-side innovations, this report looks more closely and reviews available data for two additional and related criteria that influences the climate mitigation impact of key technological innovations: cost and market adoption. This report reviews selected technological innovations for reducing demand for the buildings, transport, and industry sectors by focusing on three key elements. These include 1) cost data and energy/emission reduction potential, 2) current and projected market adoption data and barriers to deployment, and 3) specific case studies of successful market deployment and savings. In terms of policies and programs focused on reducing energy demand through new technical measures or technologies, there is growing focus (particularly within Europe) on supporting the concept of energy sufficiency. Across many sectors, reviews of existing and proposed policies and programs related to energy sufficiency in Europe show that regulations and fiscal or economic measures appear to be the most common policy instrument types, with limited policy instruments for education, research and development and voluntary agreements. But the diverse distribution of policy instrument types and sectoral coverages indicate that energy sufficiency is a diverse policy field with multiple options for implementation and effect.

A study on the low-carbon development path of civil aviation considering the impact of high-speed rail planning in China

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Abstract: Growth in China's transportation sector has resulted in a rapid increase in both energy demand and carbon emissions, particularly in the civil aviation sub-sector, which is the most difficult part of the transportation sector to decarbonize in the quest for carbon neutrality. This study focuses on the low-carbon development path of China's civil aviation sub-sector using the China Transportation Energy Model. The approach used in this study combines historical operational data and passenger fleet data. A framework is established to analyze the optimal development pathway toward near-zero emissions for China's civil aviation sub-sector from a fleet perspective. The timing and scale of the introduction of key low-carbon technologies and alternative fuel technologies are quantified.

The main findings are as follows. The optimal low-carbon development pathway for China's civil aviation sub-sector involvers a combination of retrofitting technology, operational management technology, alternative fuel technology, and improvements in energy efficiency, enabling a 10.9% decrease in the costs involved in achieving the goal of near-zero emissions compared with those when only biomass fuel is used. Disruptive airframe technologies will reduce emissions reduction costs by 10.1%. As the price of hydrogen continues to fall, hydrogen-powered aircraft will become a cost-effective choice in the long term. However, the substitution effect of high-speed rail will make hydrogen-powered aircraft less attractive.

The results of this study suggest that, in the long run, multiple low-carbon technologies should be combined to support the further de-carbonization of China's civil aviation sub-sector.

Keywords: civil aviation, transportation sector, low-carbon development; fleet; CO_2 emissions reduction

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Chapter 1 Introduction

1.1 The Need for Low-carbon Development of China's Civil Aviation Sub-sector

The transportation sector plays an important role in China's economic development. Since reform and opening up, China's transportation sector has made significant progress [1], with passenger numbers and freight volumes maintaining rapid growth, along with the development of the civil aviation sub-sector [2].

However, given China's goal of carbon neutrality by 2060, the transportation sector, which is a significant source of carbon emissions, is in urgent need of a low-carbon transformation.

The rapid expansion of China's economy has been accompanied by rapid growth in demand for air transport of both passengers and freight. During the period 2013–2019, the volume of airline passenger traffic grew from 565.68 billion person-kilometers to 1170.53 billion person-kilometers, an average annual growth rate (AAGR) of 12.9%. By contrast, during the same period, the AAGR in the overall transportation sector increased by just 5.6%. The number of domestic passenger flights in China increased from 2.78 million in 2013 to 4.611 million in 2019, an AAGR of 8.8% [3]. The *Outline of the Action Plan on Building a Powerhouse in the Civil Aviation Sector for a New Era* proposes that by 2035, the annual number of flights per capita should exceed one and aviation passengers should account for more than one-third of China's total passenger transport volume [4]. In 2019, the number of flights per capita in China was 0.5, or one-seventh and one-fifth of those in the United States and Europe, respectively. Therefore, China's civil aviation passenger and freight transport will maintain rapid growth in a long period of time.

The rapid growth in the demand for passenger flights has resulted in a rapid increase in energy consumption and carbon emissions, with civil aviation now the fastest-growing sub-sector in China's transportation sector in terms of energy consumption and carbon emissions. In terms of energy consumption in the transportation sector, the proportion represented by civil aviation increased from 7.8% in 2013 to 11.9% in 2019, while in terms of carbon emissions, the proportion represented by civil aviation increased from 7.7% in 2013 to 11.6% in 2019 [5].

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Various countries have introduced policies aimed at reducing carbon emissions by the civil aviation sub-sector. In 2009, the Civil Aviation Administration of China issued a proposal aimed at reducing energy consumption and carbon emissions per ton-kilometer and per unit revenue, respectively, by 2020 compared with 2005 levels. The 13th Five-Year Plan proposed that a green, sustainable, efficient, and energy-saving civil aviation system should be built [6]. The International Civil Aviation Organization (ICAO) plans to host regular conferences focusing on flight operations, ground operations, alternative energy, airframe technology, drive technology, ready-to-use fuels, and other emerging carbon-reduction technologies, design development paths for international civil aviation, and assist its members to achieve the action plans in relation to energy conservation and carbon reduction that have been promulgated by most member countries [7].

Although numerous countries are taking active measures to promote the low-carbon development of the civil aviation sub-sector, it remains one of the most challenging areas in the transportation sector in terms of de-carbonization. The main reasons are as follows. First, flight safety must be prioritized for passenger aircraft, and airlines are unwilling to bear the additional risks accompanying some energy saving and emissions reduction measures. For example, although single-engine taxiing can reduce energy consumption during the take-off phase, it might result in excessive wear of the engine that is used, thereby reducing its service life. Single-engine taxiing can also create problems in terms of balance. Thus this approach has not been widely promoted, even though it can lead to significant reductions in energy use and emissions. Second, there is a lack of stable and reliable alternative fuel technologies for air transport. Third, civil aviation involves high application costs of energy conservation and carbon reduction measures, without a unified plan.

Thus, China's academic community is paying considerable attention to the following questions: How many low-carbon technologies are available in China's civil aviation sub-sector, which is the most challenging area in the transportation sector in terms of de-carbonization? How should the optimal low-carbon development path for near-zero emissions by 2060 in the civil aviation sub-sector be designed in the context of the orderly advancement of the current high-speed rail plan? What scale should key low-carbon technologies reach under the optimal development pathway in future?

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1.2 Review of Studies Related to the Low-carbon Development of the Civil aviation Sub-sector

Given the rapid growth in energy consumption and carbon emissions in the civil aviation sub-sector worldwide, researchers both in China and elsewhere have developed various models and methods to enable the study of civil aviation issues. However, there have been few studies on the detailed characteristics of the civil aviation sub-sector. In terms of research scope, most studies have focused on global energy consumption and carbon emissions [8-13], with little focus on energy consumption and carbon emissions in specific countries and regions [14, 15]. Some studies have also considered civil aviation as a specific type of transport when analyzing the transportation sector [16-18].

Methods used to measure energy consumption and carbon emissions in civil aviation can be divided into two groups based on either traffic volume or distance travelled [14, 19, 20]. Most previous studies on civil aviation issues have calculated energy consumption based on traffic volume [12, 16, 21, 22]. For example, Andrew et al. (2009) [12] used this method to predict that international civil aviation carbon emissions would increase 2.1 times during the period 2005–2025. Using the Global Change Assessment Model, Pan et al. (2018) [16] analyzed China's transportation sector and calculated the energy consumption and carbon emissions of the civil aviation sub-sector based on traffic volume. Wang et al. (2017) [21] developed an analytical model to measure the energy consumption of China's civil aviation sub-sector based on both the numbers of domestic and international passengers and freight volume. However, the traffic volume method can only provide an approximate measure of the energy consumption and carbon emissions of the civil aviation sub-sector. Conversely, the distance-based method enables calculations for various aircraft models and flight segments, providing more accurate results. For instance, the ICAO has developed a carbon emissions calculation tool that is used to calculate energy consumption and carbon emissions under the current year's flight plan based on the proportion of fuel types, transportation distance, load factor, and other route-level data collected annually by the ICAO [19]. By combining the two abovementioned methods, Loo et al. (2012) [14] calculated the carbon emissions of the civil aviation sub-sector in China since 1949 and found that carbon emissions increased by about 2.9 times during the period 1992–2009.

European scholars have examined potential solutions to the problem of low-carbon development of the civil aviation sub-sector by introducing the fleet perspective and

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focusing on fleet replacement and decommissioning. Analysis from the fleet perspective enables a more detailed examination of the civil aviation sub-sector. The fleet planning model enables a detailed analysis of aircraft models based on the number of seats and the designed mileage, and considers the interactions among the fleet, airports, airlines, and government policies [8, 23-26]. For example, Schäfer et al. (2016) [23] developed the AIM2015 model to analyze the demand for different types of transport between pairs of cities, intergenerational changes, the development of low-carbon technologies in the civil aviation sub-sector, flight costs and benefits, and progress in terms of aircraft energy efficiency. The model was also used to analyze and predict global demand for various aircraft models and the potential scale of application of various low-carbon technologies. Fleet planning problems generally involve mixed-integer programming (MIP). The greater the demand in a given region, the smaller the MIP interval tolerance and the more difficult the solution to the problem. Therefore, previous analyses from a fleet perspective have mainly focused on airline-level fleet planning, and the MIP interval tolerance has been relatively large [25, 26]. Rosskopf et al. (2014) [25] constructed a fleet optimization model to analyze airline-level fleet planning issues and obtained the optimal fleet-management decisions based on various internal and external constraints using minimum cost and minimum emissions as objective functions. The model was edited using IBM CPLEX Optimization Studio, with the MIP interval tolerance set at 1% and the single solution time set to between 5 and 30 minutes [25]. Müller et al. (2016) [26] constructed an MIP model to analyze the optimal cost solution for a specific airline's fleet in the context of several retrofitting technology options and pressure to reduce carbon emissions, with the MIP interval tolerance set to between 0.02% and 0.5%, and the solution time set to between 30 seconds and 450 minutes [26].

Civil aviation is the most challenging industry within the transportation sector in terms of de-carbonization. In the context of low-carbon development proposed by the state, numerous studies have proposed future development paths for China's civil aviation sub-sector. Nevertheless, the carbon emissions reduction measures considered in previous studies have mainly involved improved energy efficiency and the use of biomass fuel, rather than considering comprehensive emissions reduction measures. Furthermore, scenario analysis has predominantly been applied in these studies. For example, Zhou et al. (2016) [15] estimated future energy consumption and carbon emissions under various scenarios using the traffic volume method, and proposed a development path for the civil

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aviation sub-sector based on the use of alternative fuels. Liu Junling (2018) [27] used scenario analysis to estimate future energy consumption and carbon emissions in China's transportation sector and found that the use of biomass fuel will reduce CO_2 emissions by about one billion tons by 2050.

Numerous emissions reduction measures have been introduced by the civil aviation sub-sector, such as energy efficiency improvements, retrofitting technology, operational management technology, alternative fuels, and next-generation airframes [28]. Lynnette et al. (2019) [8] and Schäfer et al. (2016) [23] analyzed the existing carbon reduction technologies used in the civil aviation sub-sector, which consisted of three main types: passenger aircraft retrofitting, fleet management changes, and alternative fuels. Retrofitting technology mainly involves energy saving approaches that can be applied to aircraft that have been in service for a long period, such as winglets. Fleet management changes are aimed at improving the overall energy efficiency of the fleet, for instance, by optimizing the taxiing process of passenger aircraft at airports and reducing the fleet's average waiting time on the ground. Alternative fuel technologies that have been considered in previous studies have mainly been ready-to-use biomass fuel.

1.3 Current Energy Consumption and Carbon Emissions in China's Civil Aviation Sub-sector

In China's civil aviation sub-sector, passenger aircraft are divided into three categories: regional, narrow-body, and wide-body aircraft [29]. Each category can be further divided by size into small, medium, and large aircraft. The resulting nine subcategories have seat numbers ranging from 0–50 to 51–80, 81–100, 101–130, 131–150, 151–182, 183–260, 261–300, and 301–500. Typical aircraft models in the various categories include the EMB-145, CRJ700, EMB-190, A319, A320, B737-800, A3320-200, A330-300, and B777-300ER.

China's civil aviation sub-sector has grown rapidly, with the total number of passenger aircraft in China's civil aviation fleet growing from 2,650 in 2015 to 3,639 in 2018 [29]. The fleet is dominated by narrow-body aircraft; in 2018, small, medium, and large narrow-body aircraft accounted for 5.3%, 25.6%, and 51.8%, respectively, of the total passenger fleet, while in 2015, they accounted for 7.6%, 25.5%, and 49.4%, respectively, of the total passenger fleet. In recent years, the relative proportions of large and medium-sized narrow-body aircraft and medium-sized wide-body aircraft have

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increased. In 2018, large narrow-body aircraft and medium-sized wide-body aircraft accounted for 51.8% and 6.4%, respectively, of the total fleet.

The energy consumption and carbon emissions of the civil aviation sub-sector in China have maintained continuous growth. Energy consumption by domestic passenger flights increased from 25.6 million tons of aviation fuel in 2015 to 37.41 million tons in 2018 [30]. The energy consumption and carbon emissions of China's civil aviation sub-sector during the period 2015–2018. Energy consumption by domestic passenger flights in China was calculated using flight data for the period 2015–2018 collected from the Variflight database, which contains information such as city of departure, city of arrival, and aircraft model in relation to each flight. The energy consumption data for each flight and each aircraft model was obtained from the results of research by He Jicheng (2016) [22], the ICAO (2016) [19], and EUROCONTROL (2018) [30]. Given the negligible differences in the operating conditions of specific aircraft and engine models around the world, where data for specific aircraft models were unavailable, we used the ICAO data.

Regional, narrow-body, and wide-body passenger aircraft account for 89.7%, 3.7%, and 6.6%, respectively, of the total number of domestic passenger flights in China. In terms of flight distance, flights of between 1,000 km and 2,000 km account for 49.8% of all flights, with only a few multi-segment flights of 10,000 km or more.

Narrow-body passenger aircraft are responsible for most of the energy consumption and CO_2 emissions of China's domestic civil aviation sub-sector. During the period from 2015 to 2018, energy consumption and CO_2 emissions by small, medium, and large regional passenger aircraft, small, medium, and large narrow-body passenger aircraft, and small, medium, and large wide-body passenger aircraft were 0.6%, 0.2%, 2.2%, 6.5%, 28.8%, 55.6%, 0.1%, 2.8%, and 3.2%, respectively. Wide-body passenger aircraft accounted for the lowest proportion of energy consumption and CO_2 emissions. In terms of flight distance, flights of between 1,000 km and 2,000 km accounted for 56.3% of total energy consumption and CO_2 emissions, those of between 2,000 km and 3,000 km accounted for 20.7%, and those of less than 500 km or more than 10,000 km accounted for just 2.9%. During the period 2015–2018, narrow-body passenger aircraft were responsible for the largest growth in energy consumption and carbon emissions, while regional passenger aircraft experienced negligible growth in energy consumption and carbon emissions.

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1.4 Research Aim and Study Structure

Previous studies analyzing the energy consumption and CO_2 emissions of the civil aviation sub-sector have mainly used the traffic volume method, which does not provide a detailed description of the civil aviation sub-sector. The main emissions reduction technology considered using this method is the use of biomass fuel.

The main contributions of this study include establishing a civil aviation analysis framework based on a fleet perspective, developing a fleet planning and analysis platform based on the technical parameters of historical fleet data and low-carbon development to determine the optimal development path for civil aviation toward the goal of near-zero emissions in the context of high-speed rail development, quantifying the scale of key low-carbon technologies such as hydrogen-powered aircraft and biomass fuel at key time points, and exploring the effect of key factors such as the hydrogen price on the development path of the civil aviation sub-sector.

The rest of the paper is organized as follows. Chapter 2 introduces the methodology used in this study, including analytical ideas and model design. Chapter 3 introduces the main data used, assumptions made, and various development scenarios. Chapter 4 presents and discusses the results. Chapter 5 concludes.

Chapter 2 Model and Methodology

2.1 Model Design Ideas

The optimal path for the development of China's civil aviation sub-sector is analyzed using historical air route-level operational data from a fleet perspective. This takes into account the costs and benefits of low-carbon technologies such as retrofitting, operational management changes, advances in passenger aircraft design, and alternative fuels. In aiming to minimize the total cost of fleet operations including fuel costs, purchase costs, and maintenance costs, it solves the problem of MIP, presents the optimal plan for the development of the civil aviation sub-sector to achieve a carbon emissions reduction target, and presents optimal choices regarding fleet composition, purchase costs, operating costs, and maintenance costs in terms of contributions to emissions reduction. Fleet composition and the scale of application of low-carbon technologies are used as the

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inputs to calculate the transportation sector's total energy consumption and carbon emissions. The substitution percentage of civil aviation flights in each distance segment obtained through the analysis of the substitution effect of high-speed rail on civil aviation passenger transport will be used as the input for this part of the research and for judging the future demand and composition of civil aviation transport.

2.2 Introduction of the Model

The low-carbon development model identifies the optimal route for the development of the civil aviation sub-sector from a fleet perspective based on cost minimization. Using historical ownership and operational data for various types of aircraft, this model determines the optimal Chinese fleet in terms of purchase, decommissioning, retrofitting, management, and fuel use. In this section, we introduce the study framework, as well as the objective functions, variables, and main constraints.

2.2.1 Energy consumption

Using 2015 as the base year, we use the civil aviation sub-model to calculate the energy consumption and carbon emissions of passenger and freight aircraft when they take off from and land at airports in 31 Chinese provinces. Given the low volume and low rate of growth of freight transport, this sub-model does not provide a detailed classification and description of air freight transport. Regarding passenger flights, the sub-model calculates the energy consumption of wide-body, narrow-body, and regional passenger aircraft, which have more than 250 seats, between 100 and 200 seats, and less than 100 seats, respectively. The sub-model takes into account the use of aviation kerosene, biomass fuel, electricity, and hydrogen.

The calculation principle of the civil aviation sub-model is shown in Fig. 1. Inputs include historical fleet ownership and composition, predicted future sales and composition, historical macroeconomic data, economic efficiency and activity level of fuel, and energy carbon intensity. Energy consumption during aircraft operation is divided into two phases: take-off and cruise. Energy consumption during the take-off phase is based on the take-off power of the engines used by each aircraft model and the average take-off time. Energy consumption during the cruise phase is based on the equivalent number of seats, flight distance, and the design mileage of various aircraft models[8, 31, 32]. Because the energy efficiency data for some aircraft models do not include

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fuel consumption during the cruise phase, we used the air route fuel model to simulate the energy consumption of flights over various distances. Based on the activity of a single aircraft representing each aircraft model, the average efficiency was calculated using the energy consumption model. The energy consumption for a single flight was compared with the default energy consumption values for different flight distances provided by the ICAO [19]. For aircraft types whose energy consumption had been calculated in previous studies, we used those figures to represent their energy efficiency.

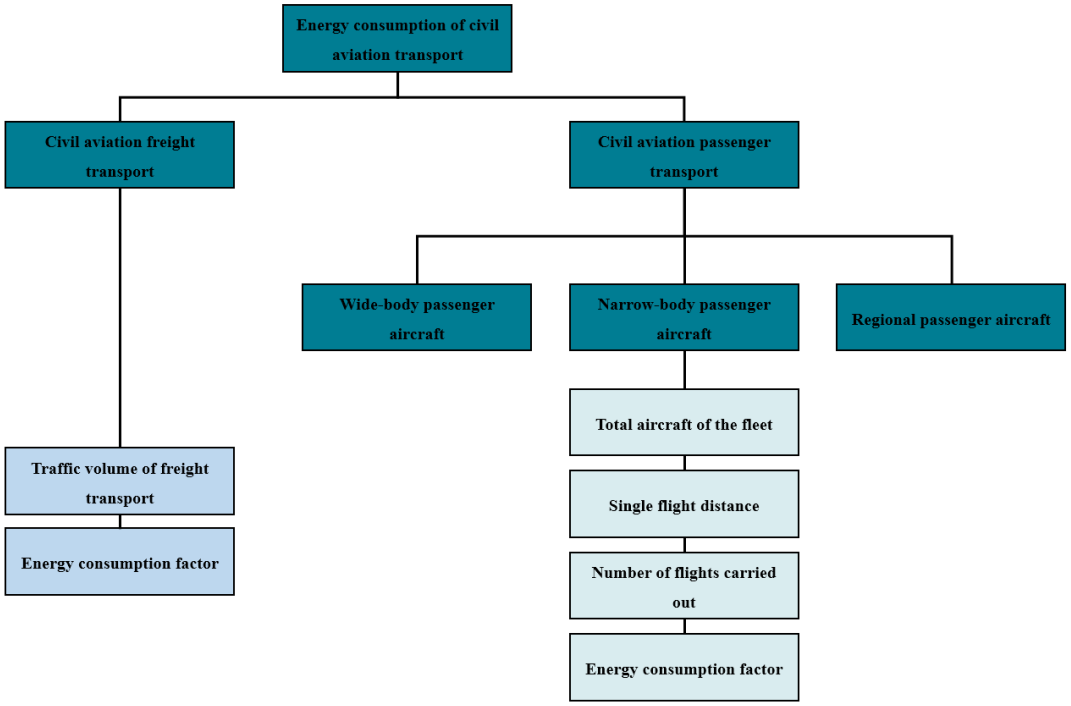


Fig. 1 Calculation principle of the civil aviation sub-model

2.2.2 Study framework

The study framework is shown in Fig. 2. Both historical ownership data and flight data for each aircraft model were used. Total costs were divided into four categories: purchase costs, fuel costs, retrofitting technology and management technology costs, and maintenance costs [26, 33]. Fuel costs were further divided into the taxiing and take-off phase and the cruise phase. No further classification is made into the fuel costs for the take-off phase in this module. Fuel costs included the costs of traditional aviation kerosene, biomass fuel, hydrogen, and electricity.

Purchase costs included the cost of acquiring new aircraft, including traditional fuel-powered aircraft, hydrogen-powered aircraft, and electric-powered aircraft, and the

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residual income following decommissioning of the aircraft. Five aircraft purchase options were considered: previous-generation models (i.e. traditional fuel-powered models produced before 2015), current-generation models (i.e. models that commenced production and commercial use around 2020), next-generation models (i.e. models that will start to be commissioned in 15 to 20 years), hydrogen-powered aircraft, and electric-powered aircraft. In general, a new generation of passenger aircraft appears every 15 to 20 years, and all previous passenger aircraft models had basically been replaced by 2020. Thus, the next-generation passenger aircraft that will start to be commissioned in 15 to 20 years were included [23, 28]. The available time of purchase options for the five types of passenger aircraft considered in this module is preset in this research according to technological development and the types of aircraft still under production as announced by aircraft manufacturers.

Fuel costs include the cost of aviation kerosene and biomass fuel for the operation of traditional fuel-powered aircraft, the cost of hydrogen used in the operation of hydrogen-powered aircraft, and the cost of electricity used by electric-powered aircraft.

Retrofitting technology refers to a range of technologies applied to aircraft that are more than 1-year-old with the aim of improving energy efficiency. Management technology refers to a range of operational measures applied at the fleet level with the aim of improving overall operational efficiency. The application of retrofitting and management technologies involves installation costs and ongoing annual maintenance costs.

Inputs include the ownership of the fleet groups of varying ages in the Chinese fleet, fleet energy efficiency data, the costs and benefits of various carbon emissions reduction technologies, oil prices, hydrogen prices, and the near-zero emissions constraints on the civil aviation sub-sector. Outputs for each phase include the size and composition of the fleet, the ownership and composition of the fleet, the scale of application of various retrofitting technologies, the new installation scale for various retrofit technologies, the scale of application of various management measures, the scale of application of biomass fuel, and the numbers of various aircraft models that are decommissioned.

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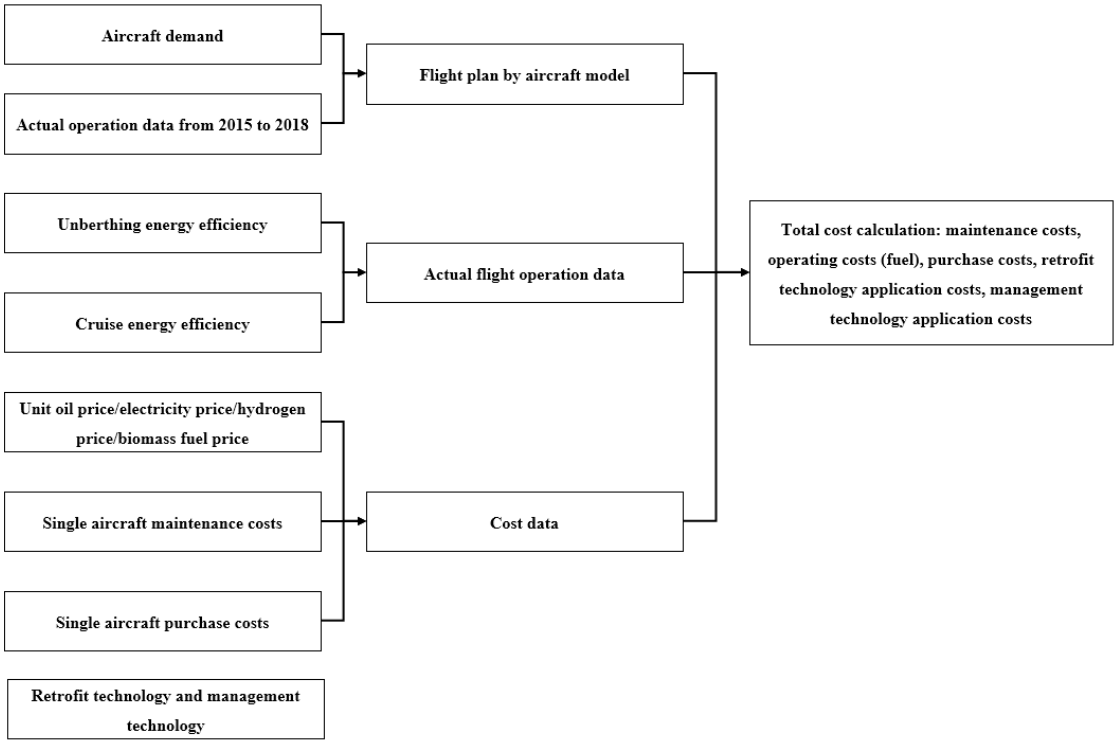


Fig. 2 Study framework

2.2.3 Main calculation principle

The energy consumption of the civil aviation sub-sector was obtained by summing the energy consumption of freight aircraft, wide-body passenger aircraft, narrow-body passenger aircraft, and regional passenger aircraft. The energy consumption of freight aircraft was obtained by multiplying the freight volume by the energy consumption factor per unit of volume. The energy consumption of passenger aircraft was obtained by multiplying the number of fleets composed of different types of aircraft by the average flight distance, by the flight frequency each aircraft, by the energy consumption intensity as follows:

$$EC_t = \sum_{r \in R} \sum_{i=1}^{3} (PS_{i,r,t} \times Freq_{i,r,t} \times EIPA_{i,r,t}) + AFT_t \times ECF_t \ , \qquad (1)$$

where *EC* represents the total energy consumption of the industry, *i* represents the various passenger aircraft types (wide-body, narrow-body, and regional), *r* represents the technical route of fuel and aircraft type in the fleet, *PS* represents the number of fleets, *Freq* represents the flight frequency of a single aircraft, *EIPA* represents the energy consumption of a single aircraft during a single flight, *AFT* represents the freight traffic volume, and *ECF* represents the energy consumption factor for freight transport. CO_2

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emissions were obtained by multiplying aviation kerosene consumption by the emissions factor.

The energy efficiency of each passenger aircraft model was obtained by summing average fuel consumption during the take-off phase and average fuel consumption during the cruise phase, as follows:

$$EIPA_{i,r,t} = EI_LTO_{i,r,t} + EI_Cruise_{i,r,t}, \quad (2)$$

where *EI_LTO* represents energy consumption during the take-off phase and *EI_Cruise* represents energy consumption during the cruise phase. Energy consumption during the take-off phase was calculated based on the average engine power of the passenger aircraft and the average operation time during take-off. The average operation time was obtained from the results of previous studies on domestic civil aviation, and the average engine power was obtained from the ICAO's database of aircraft energy consumption and carbon emissions, as follows:

$$EI_LTO_{i,r,t} = \sum_{v \in V} FuelFlow_{i,r,v,t} \times Duration_{i,r,v,t}, \quad (3)$$

where *FuelFlow* represents the engine fuel flow rate for each process, including taxiing, climbing, landing, and positioning, during the take-off phase; *Duration* represents the average duration of each process; and *v* represents each process during the take-off phase. Fuel consumption during the cruise phase was calculated using the flight fuel consumption model, which calculates flight energy consumption based on historical flight energy consumption data for various aircraft models in combination with the equivalent number of seats, the flight distance, and the design mileage. There is an approximately linear relationship between the average fuel consumption at different flight distances and the flight distance, and the regression parameters are related to the design mileage and the equivalent number of seats [31, 32]. In view of the consistency of aircraft types worldwide, the average fuel consumption during the cruise phase was also compared with the figures included in reports from foreign research institutions (such as the energy consumption data in reports published by the ICAO, EUROCONTROL, and other agencies) and related studies [30, 32, 34-36].

The relationship between *EI_Cruise*, the average energy consumption of each aircraft model over different flight distances and during the take-off and cruise phases, the equivalent number of seats, and the design mileage is shown in Formula (4). There is

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a functional relationship among related parameters, $Se_{eq,i}$, the equivalent number of seats, and *DeDist*, the design mileage. *AvDist* represents the average flight distance.

$$EI_Cruise_{i,r,t} = f_1(Se_{eq,i,r,t}, DeDist_{i,r,t}) \times AvDist_{i,r,t} + f_2(Se_{eq,i,r,t}, DeDist_{i,r,t}) \quad (4)$$

Possible measures aimed at achieving a reduction in the carbon emissions intensity of passenger aircraft are shown in Formula (5) [23], where *EM* represents the carbon dioxide emissions of a single flight, *RPK* represents revenue per passenger-kilometer, *EF* represents the fuel emissions factor, *HV* represents the low caloric value of the fuel, *FFlow* represents the energy consumption per unit of engine power output, *PQ* represents the number of passengers, *Sp* represents the flight speed, *LtD* represents the lift-to-drag ratio, *FWbT* represents the fuel weight before take-off, and *AWT* represents the gross weight of the aircraft at take-off. Thus, the following measures can be taken to reduce carbon emissions during the operation of passenger aircraft: (1) reducing the carbon content of fuels, such as biomass fuel and other alternative fuels, or reducing the carbon dioxide emissions factor; (2) improving the energy efficiency of the engine or reducing energy consumption per unit of power output, such as commissioning new-generation engines; (3) increasing the number of passengers carried per aircraft by taking operational management measures to increase the load; (4) increasing the overall energy efficiency of aircraft using retrofitting technology to reduce air resistance; and (5) reducing the gross weight and take-off weight of passenger aircraft by taking measures such as reducing the cabin weight. Based on the five main approaches to achieving emissions reductions in the civil aviation sub-sector, we divided emissions reduction measures into five categories: retrofitting, operational management technologies, alternative fuels, new-generation aircraft, and disruptive technologies. In addition, the parameter setting for various technologies and related basis are introduced in this research respectively. Cost data are expressed in constant 2010 prices. Based on the results of previous studies [33, 34, 35], the discount rate was set at 5%.

$$\frac{EM}{RPK} = EF \times \frac{HV \times FFlow}{PQ \times Sp \times LtD} \frac{FWbT}{\ln(AWT - FWbT)} \quad (5)$$

2.2.4 Objective function, variables, and constraints

The decision-making process in relation to fleet operation is shown in Fig. 3, and includes the decision to purchase additional aircraft when demand increases, the decision

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on whether to adopt various retrofitting technologies to improve the energy efficiency of an aging fleet, the decision on whether to adopt various operational management technologies in relation to the current fleet, and the decision on whether to purchase aircraft that use alternative fuel technologies.

The variables include the purchase quantity of various types of aircraft in the current period, the number of aircraft decommissioned in the current period, the scale of application of various types of retrofitting technologies and operational management measures in relation to various aircraft models and the scale of application of biomass fuel. The variables and their definitions are shown in Table 1. The subscript *i* represents the generation type and alternative fuel type for each aircraft, *j* represents the aircraft category based on its size and designed flight mileage, *k* represents the age of specific aircraft in the current period, *t* represents the number of periods, *m* represents a specific retrofitting technology, and *n* represents a specific operational management technology. *I* represents the set of all aircraft generation types and alternative fuel types to which *i* belongs, *J* represents the set of all aircraft sizes and types, *K* represents the maximum service life of the aircraft, *T* represents the total time period under consideration, *M* represents the set of all available retrofitting technologies, and N represents the set of all available operational management technologies.

Aircraft using alternative fuels might experience service life decay. For example, hydrogen-powered aircraft might see a decrease in the annual number of flights. Thus, an operating frequency decay coefficient is included. Furthermore, the range of aircraft using alternative fuels might be limited. For example, electric-powered aircraft might be unable to undertake long-distance flights or carry as many passengers as conventional fuel-powered aircraft because of their limited battery capacity. Thus, the range of alternative fuel-powered aircraft is preset based on the results of the literature review and related studies. Additionally, maintenance costs will increase over time, and thus a deterioration rate is used to reflect the effect of aircraft age on maintenance costs.

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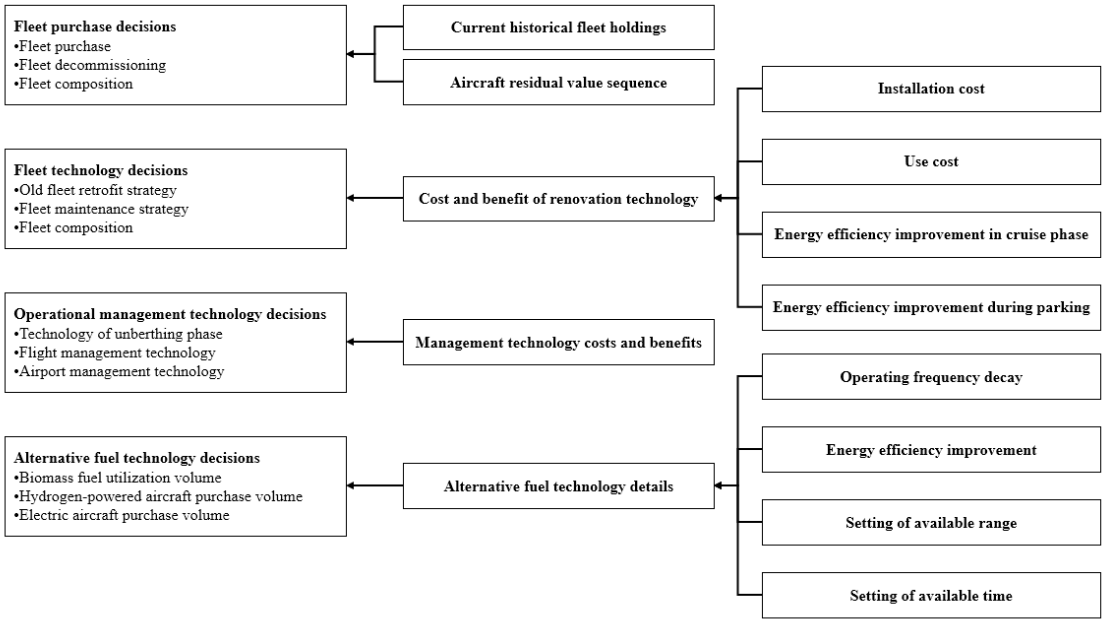


Fig. 3 Variables and related parameters

Table 1 Variables and their definitions

Decision variable	Description
$Pur_{i,j,t}$	Amount of passenger aircraft of types *i* and *j* purchased in period *t*
$Liqui_{i,j,k,t}$	Amount of types *i* and *j* passenger aircraft aged *k* and actively decommissioned in period *t*
$Retro_{i,j,k,m,t}$	Scale of types *i* and *j* passenger aircraft at the age of k applying the retrofit technology *m* in period *t*
$Ini_Retro_{i,j,k,m,t}$	Amount of types *i* and *j* passenger aircraft at the age of k starting to apply the retrofit technology m in period *t*
$Man_{i,j,k,n,t}$	Scale of types *i* and *j* passenger aircraft applying the management technology *n* and aged *k* in period t
$Ini_Man_{i,j,k,n,t}$	Amount of types *i* and *j* passenger aircraft at the age of k starting to apply the application management technology *n* in period *t*
$Dec_Retro_{i,j,k,m,t}$	0/1variable of whether the retrofit technology is applied to types *i* and *j* passenger aircraft in period *t*
$Dec_Man_{i,j,k,n,t}$	0/1 variable of whether the management technology is applied to types *i* and *j* passenger aircraft in period *t*
Bio_Range_t	Application range of ready-to-use biomass fuel in period *t*

The goal is to minimize the operating costs of China's civil aviation passenger fleet, that is, the sum of purchase costs, retrofitting technology costs, management technology

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costs, fuel costs, and maintenance costs during the 41 periods from 2020 to 2060 as follows:

$$Min.\ TC = \sum_{t \in T} \left(CPur_t - CLqd_t + CRetrofit_t + COp_t + CMaintain_t + CFuel_t \right) \cdot (1+d)^{-t}, \quad (6)$$

where *TC* represents total operating costs, *CPur* represents the cost of newly purchased aircraft, *CLqd* represents the residual recovery from decommissioned aircraft, *CRetrofit* represents the cost of retrofitting technology, *COp* represents the cost of operational management technology, *CMaintain* represents maintenance costs, *CFuel* represents fuel costs, and *d* represents the discount rate.

We set an upper service limit after which an aircraft is automatically decommissioned, rather than using the theoretical maximum service period. All variables were required to satisfy the positive integer condition, including the numbers of each aircraft model purchased and decommissioned, and whether each aircraft in each period adopts the 0/1 decision variables of a certain technology.

Chapter 3 Data, Assumptions and Scenario Design

3.1 Emissions Reduction Measures and Parameter Settings

3.1.1 Retrofitting technology

With the emergence of new standards, technologies, and engines, as well as fluctuations in oil prices, the operational and economic efficiency of aging passenger aircraft might not be optimal. Thus, retrofitting technology might be used in an attempt to improve aircraft performance [104, 107, 175].

3.1.1.1 Blended winglets

Blended winglets are added to the wingtips of aircraft to reduce drag when the aircraft is cruising [36]. For the purposes of this study, we assumed that blended winglets can be used as a retrofitting technology option for all short- and medium-haul aircraft manufactured before 2015 [37-39]. However, large wide-body passenger aircraft cannot be equipped with blended winglets. The parameters, costs, and benefits related to the use of this technology on various types of aircraft are shown in Table 2. Based on previous studies and technical data published by Boeing, Airbus, and regional passenger aircraft

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manufacturers [23, 33, 40, 41], the installation cost of blended winglets ranges from 80,000 to 140,000 US dollars, and the purchase cost ranges from 750,000 to 1.8 million US dollars. Blended winglets only affect energy efficiency during the cruise phase, and have no effect on energy efficiency during the take-off phase. We assumed that this technology was available in 2015 because various companies had already provided retrofitting services at that time.

Table 2 Parameters, costs, and benefits related to blended winglets

Aircraft type	Typical aircraft model	Available time	Purchase costs (ten thousand US dollars)	Installation costs (ten thousand US dollars)	Cruise energy efficiency improvement (%)
Small-sized regional passenger aircraft	EMB-145	2015	75	8	4
Medium-sized regional passenger aircraft	CRJ700	2015	90	8	4
Large-sized regional passenger aircraft	EMB-190	2015	105	8	4
Small-sized narrow-body passenger aircraft	A319	2015	120	10	4.5
Medium-sized narrow-body passenger aircraft	A320	2015	135	10	4.5
Large-sized narrow-body passenger aircraft	B737-800	2015	150	10	4.5
Small-sized wide-body passenger aircraft	A3320-200	2015	165	14	3.5
Medium-sized wide-body passenger aircraft	A330-300	2015	180	14	3.5

3.1.1.2 Engine updating and upgrading

Compared with conventional engine models, new engine models can improve overall energy efficiency by 10 to 15% [23, 26, 33]. In this study, we assumed that engine updating and upgrading was a retrofitting technology option for models produced before 2015 [26, 33]. Based on a comparison of the parameters of previous-generation and next-

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generation engine models [42, 43] and the results of our literature review [44, 45], we determined the parameters for the costs and benefits of the use of this technology, as shown in Table 3. Engine replacement affects energy efficiency during both the cruise and take-off phases. Given that neither Boeing nor Airbus has explicitly listed engine replacement as a commercial project, we assumed that this technology could be introduced by 2023, with small passenger aircraft retrofitted prior to large passenger aircraft.

Table 3 Parameters related to engine updating and upgrading

Aircraft type	Typical aircraft model	Available time	Purchase costs (ten thousand US dollars)	Installation costs (ten thousand US dollars)	Cruise energy efficiency improvement (%)
Small-sized regional passenger aircraft	EMB-145	2021	710	25	10
Medium-sized regional passenger aircraft	CRJ700	2021	850	25	10
Large-sized regional passenger aircraft	EMB-190	2022	985	25	10
Small-sized narrow-body passenger aircraft	A319	2022	1120	45	13
Medium-sized narrow-body passenger aircraft	A320	2023	1260	45	13
Large-sized narrow-body passenger aircraft	B737-800	2023	1400	45	13
Small-sized wide-body passenger aircraft	A3320-200	2023	1536	65	15
Medium-sized wide-body passenger aircraft	A330-300	2023	1660	65	15

3.1.1.3 Electric-powered taxiing system

An electric-powered taxiing system enables aircraft to taxi using the electric-powered drive system on either the front or main landing gear of the aircraft, rather than using the aircraft's engines [26, 27]. The system is driven by an auxiliary power unit,

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reducing the aircraft engines' operating time and enabling energy conservation and emissions reduction [46-48].

This technology was introduced to the Chinese fleet in 2020. The total cost of an electric-powered taxiing system of 250,000 to 550,000 US dollars was based on information presented on providers' websites and parameters used in previous studies [8, 23, 26, 33, 49]. The "Energy efficiency improvement" column in Table 4 refers to the overall energy conservation effect after considering the increase in energy consumption during the cruise phase as a result of the increased airframe weight, as well as the energy conserved during the taxiing phase.

Table 4 Parameters related to the electric-powered taxiing system

Aircraft type	Typical aircraft model	Available time	Total costs (ten thousand US dollars)	Energy efficiency improvement (%)
Small-sized regional passenger aircraft	EMB-145	2023	25	1.8
Medium-sized regional passenger aircraft	CRJ700	2023	29	1.8
Large-sized regional passenger aircraft	EMB-190	2023	34	1.8
Small-sized narrow-body passenger aircraft	A319	2023	45	2.8
Medium-sized narrow-body passenger aircraft	A320	2023	50	2.8
Large-sized narrow-body passenger aircraft	B737-800	2023	55	2.8

3.1.1.4 Cabin weight reduction

Cabin weight reduction in relation to passenger aircraft mainly refers to the use of lightweight materials to reduce the weight of non-essential components in the cabin [26]. In this study, only the effect of replacing components inside the cabin, rather than the reduction in airframe weight through the adoption of new materials is considered. The parameters related to cabin weight reduction are shown in Table 5. Cost and energy efficiency parameters were based on the results of research by Muller et al. (2018) [26], Dray et al. (2018) [33], and the World Bank (2012) [50].

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Table 5 Parameters related to cabin weight reduction

Small-sized regional passenger aircraft	EMB-145	2015	20	1.3
Medium-sized regional passenger aircraft	CRJ700	2015	25	1.4
Large-sized regional passenger aircraft	EMB-190	2015	32	1.6
Small-sized narrow-body passenger aircraft	A319	2015	45	1.8
Medium-sized narrow-body passenger aircraft	A320	2015	62	2.1
Large-sized narrow-body passenger aircraft	B737-800	2015	80	2.1
Small-sized wide-body passenger aircraft	A3320-200	2015	125	2.2
Medium-sized wide-body passenger aircraft	A330-300	2015	160	2.2
Large-sized wide-body passenger aircraft	B777-300ER	2015	230	2.2

3.1.2 Operational management technology

Ground or airspace congestion can result in aircraft operating in a suboptimal state [23, 51, 52]. Operational management technology refers to specific technologies aimed at improving the efficiency of air traffic and the operating efficiency of airports.

3.1.2.1 Air traffic management system

Air traffic management systems synchronize, coordinate, and manage air traffic activity based on available space, time, and other information related to the overall safety and economic efficiency of operations [53, 54].

We used the results of previous studies [23, 33, 52, 54-57] to set our cost and benefit parameters, as shown in Table 6. These studies used flight operation data from the United States. Because China's airspace is more densely populated than that of the United States, the parameter settings for energy efficiency improvement were conservative. This technology only affects energy consumption during the cruise phase. China proposed a modernized development strategy for air traffic control during the period 2016–2030 with the aim of achieving the goals of performance-based service, joint military and civilian use of airspace, and real-time airspace flow management. Thus, we assumed that this technology will be available in 2025.

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Table 6 Parameters related to the air traffic management system

Aircraft type	Typical aircraft model	Available time	Total costs (ten thousand US dollars)	Energy efficiency improvement (%)
Small-sized regional passenger aircraft	EMB-145	2025	7.0	2.8
Medium-sized regional passenger aircraft	CRJ700	2025	7.2	3.0
Large-sized regional passenger aircraft	EMB-190	2025	7.5	3.1
Small-sized narrow-body passenger aircraft	A319	2025	7.8	3.4
Medium-sized narrow-body passenger aircraft	A320	2025	8.1	4.9
Large-sized narrow-body passenger aircraft	B737-800	2025	8.3	5.8
Small-sized wide-body passenger aircraft	A3320-200	2025	10.0	6.3
Medium-sized wide-body passenger aircraft	A330-300	2025	11.2	7.0
Large-sized wide-body passenger aircraft	B777-300ER	2025	13	8

3.1.2.2 Single-engine taxiing

Single-engine taxiing refers to the use of either two engines on four-engine aircraft or one engine on two-engine aircraft during taxiing [58]. As can be seen from Table 7, we believe that this technology is not yet in widespread use, and only affects energy efficiency during the take-off phase.

Table 7 Parameters related to single-engine taxiing

Aircraft type	Typical aircraft model	Available time	Total costs (ten thousand US dollars)	Taxiing efficiency improvement （%）
Small-sized regional passenger aircraft	EMB-145	2020	1	20
Medium-sized regional passenger aircraft	CRJ700	2020	1.2	22
Large-sized regional passenger aircraft	EMB-190	2020	1.4	26
Small-sized narrow-body passenger aircraft	A319	2025	1.6	32
Medium-sized narrow-body passenger aircraft	A320	2025	1.9	35

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Large-sized narrow-body passenger aircraft	B737-800	2025	2.1	36
Small-sized wide-body passenger aircraft	A3320-200	2025	3.6	36
Medium-sized wide-body passenger aircraft	A330-300	2025	4.8	38
Large-sized wide-body passenger aircraft	B777-300ER	2025	6	40

3.1.2.3 Airport ground congestion management

Airport ground congestion can lead to increased taxiing time, and thus increased energy consumption. Applying airport ground congestion management strategies can make the introduction rate of an airport approach the upper limit that can be reached by the airport [59, 60].

The parameters related to airport ground congestion management technology are shown in Table 8. Based on the effects of implementation of ground congestion management technology at major airports in the United States and China [59, 61-63], we assumed that the average taxiing time was reduced by 15%. Because airlines are charged fees for the application of this technology, we assumed that the costs and revenue were identical for each aircraft model. This technology only affects energy consumption during the take-off phase. According to previous studies [23, 33], the cost of this technology was based on the cost of realizing the navigation performance necessary for airport congestion management technology.

Table 8 Parameters related to airport ground congestion management

Aircraft type	Typical aircraft model	Available time	Total costs (ten thousand US dollars)	Taxiing efficiency improvement （%）
Small-sized regional passenger aircraft	EMB-145	2020	2	15
Medium-sized regional passenger aircraft	CRJ700	2020	2	15
Large-sized regional passenger aircraft	EMB-190	2020	2	15
Small-sized narrow-body passenger aircraft	A319	2020	2	15
Medium-sized narrow-body passenger aircraft	A320	2020	2	15
Large-sized narrow-body passenger aircraft	B737-800	2020	2	15

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Small-sized wide-body passenger aircraft	A3320-200	2020	2	15
Medium-sized wide-body passenger aircraft	A330-300	2020	2	15
Large-sized wide-body passenger aircraft	B777-300ER	2020	2	15

3.1.3 Alternative fuel technologies

Alternative fuel technologies in relation to civil aviation are divided into three categories: biomass fuel, hydrogen, and electricity.

3.1.3.1 Biomass fuel

Biomass fuel is a ready-to-use alternative fuel that is likely to be widely used in the civil aviation sub-sector over the next few years because there is no need to change either the aircraft structure or ground storage and transportation facilities.

In this study, we focused on the price of hydrogenated biomass fuel [64, 65]. Based on the cost of biomass aviation fuel preparation and the predicted future costs of various options outlined in previous studies [64, 66-68], and assuming a decline in the cost of biomass fuel in the future, we assumed a gradually declining future cost for biomass fuel, as shown in Table 9. The cost of biomass fuel in 2060 will fall by 55% compared with the cost in 2020.

Table 9 Prices of biomass aviation fuel (US dollars/ton)

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Unit price	2750	2145	1780	1685	1530	1378	1346	1309	1250

3.1.3.2 Electric-powered aircraft

Electric-powered aircraft are one obvious means of achieving the goal of zero carbon emissions in the future [69].

In this study, it is assumed that only short-haul regional passenger aircraft will be electric-powered, with no electric-powered narrow- and wide-body passenger aircraft. Based on the published plans of major aircraft manufacturers and relevant studies [70-73], and considering current cell technology bottlenecks, we assumed that electric-powered aircraft will be available for regional passenger aircraft fleets in 2035. Based on studies of the economic efficiency of electric-powered aircraft [69], the purchase costs of electric-

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powered aircraft are 20% higher than those of traditional aircraft. However, electric-powered aircraft will not produce any carbon emissions. Flight energy consumption data were obtained from previous studies [69, 74, 75].

3.1.3.3 Hydrogen-powered aircraft

Hydrogen is considered an important alternative fuel technology for the low-carbon development of the civil aviation sub-sector [76].

Based on the research and development plans of aircraft manufacturers and previous studies, we assumed that hydrogen-powered aircraft will become a purchase option for regional and narrow-body passenger aircraft fleets in 2035 and for wide-body passenger aircraft fleets in 2040, as shown in Fig. 4.

Hydrogen-powered aircraft will require a new aircraft structure. Important components of a hydrogen-powered aircraft include a hydrogen storage tank, a fuel distribution system, and a fuel cell system. Based on the estimated cost of each component in previous studies [76-78], we assumed that the cost of a hydrogen-powered aircraft is 31% higher than that of a conventional fuel-powered aircraft. The energy efficiency of hydrogen-powered aircraft is based on the results of previous studies and is set based on energy equivalence and through the adoption of the percentage relative to that of traditional aircraft [76, 78-81].

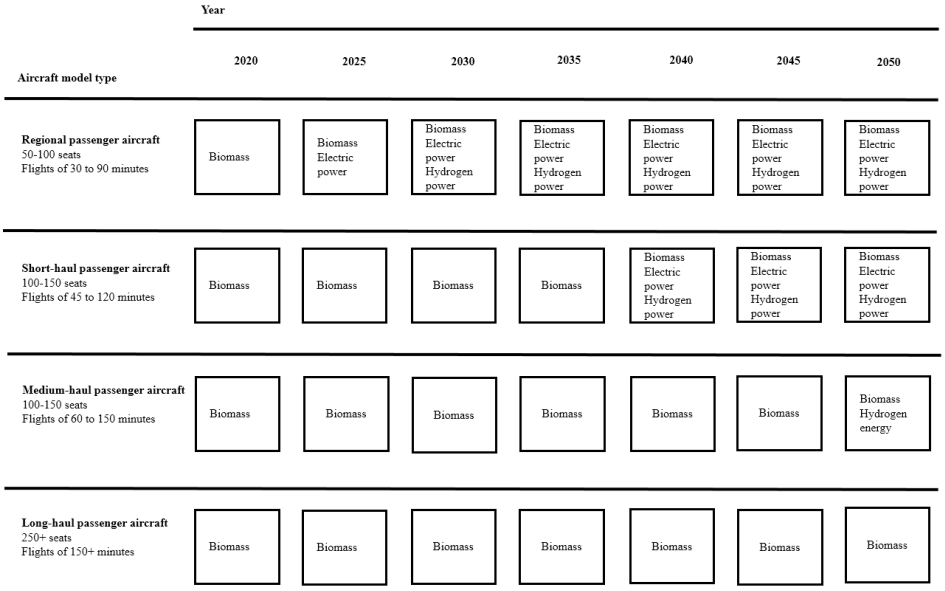


Fig.4 Alternative fuel technology introduction timeline [82, 83]

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The price of hydrogen is expected to fall significantly as the scale of production increases. Based on research by the International Energy Agency (IEA) [84], the International Renewable Energy Agency (IRENA) [85], the Hydrogen Council [86], the China EV100 [87], and the China Hydrogen Alliance [88], we assumed that the price of green hydrogen will be 25% cheaper in 2030 compared with 2020 prices, and will fall to 10 RMB/kg in 2060 (including preparation, storage and transportation costs), as shown in Table 10. Compared with previous studies, our parameter settings regarding the declining hydrogen price are conservative.

Table 10 Liquid hydrogen prices (US dollars/kg)

Year	2020	2025	2030	2035	2040	2045	2050	2055	2060
Unit price	9.2	8.4	7.0	5.8	4.7	3.5	2.3	1.8	1.5

3.1.4 Next-generation passenger aircraft

The energy efficiency of traditional passenger aircraft continues to improve. Compared with the Comet 4 passenger aircraft that were first commissioned in 1960, the B737-800 passenger aircraft designed by Boeing and the A380-800 passenger aircraft designed by Airbus have increased energy efficiency per revenue-passenger kilometer by 65% and 70%, respectively. The energy efficiency improvement of newly sold traditional aircraft that starts to be commissioned may reach 1.5%, which will significantly reduce overall emissions by passenger flights [89].

3.1.5 Disruptive aircraft technology

Given its limited potential for improvement, traditional aircraft technology will be unable to achieve the goal of near-zero emissions. By contrast, innovative changes to aircraft structure using disruptive technologies will help to facilitate the low-carbon development path of the civil aviation sub-sector.

Compared with the traditional aircraft layout involving fuel tanks and standard wings, disruptive aircraft structures include blended wings, cable-stayed wings, and box-type wings [28]. The features, research status, and predicted time of introduction of various types of technologies outlined in previous studies are shown in Table 11.

Innovative propulsion systems include propeller fan engine technology. Relying on a counter-rotating propeller to generate thrust, the propeller fan engine is situated in

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between the turboprop engine and the turbofan engine, and can increase operating energy efficiency by 26 to 30% [28, 83, 90, 91].

Table 11 Disruptive aircraft technologies

Aircraft structure	Technical feature	Year of application
Blended wing [28, 83, 92]	The wing and the airframe are highly blended, which can reduce flight resistance and noise.	2035~2040
Cable-stayed wing layout [28, 83, 93]	A support beam is installed under the wings of the passenger aircraft to improve the material utilization rate and help reduce the overall weight	2030~2035
Box-type wing [83, 94]	The connection of front and rear wings through the adoption of the tip plate reduce flight resistance, increase the lift coefficient, and reduce the structure weight	2035~2040

Because the development of various innovative technologies involves considerable uncertainty, we used aircraft equipped with blended wings and a propeller fan engine as an example of disruptive technologies and assumed that they will be available for purchase in 2035. Regarding the energy efficiency of aircraft with blended wings and a propeller fan engine, previous studies have mainly used the simulation method and found that compared with current-generation aircraft with a traditional structure, energy efficiency increases by 40% [33, 51, 91, 95, 96]. Based on generational changes in purchase costs, it is assumed that the purchase costs of disruptive aircraft will be 20% higher than those of traditional aircraft.

3.2 Additional Key Data and Important Assumptions

3.2.1 China's civil aviation passenger and freight transport demand

Data on the demand for passenger and freight transport by air in China were obtained from the *Strategic Research on Transportation Sector* report [2] and related research reports from Boeing and Airbus [97, 98]. These data were combined with economic and social development indicators, and predetermined elasticity coefficients. The estimated demand for passenger flights from 2025 to 2060 is shown in Table 12. In 2050 and 2060, the number of domestic passenger flights will reach 9.41 million and 10.303 million respectively, an increase of 2.35 times and 2.57 times compared with 2020.

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Table 12 Estimated demand for passenger flights (unit = 10,000 flights)

Year	2025	2030	2035	2040	2045	2050	2055	2060
Number of flights	501.3	630	727.9	819.7	899.3	941.0	993.5	1030.3

The estimated demand for air freight transport from 2025 to 2060 is shown in Table 13. In this study, we assumed that the freight traffic volume will initially increase, reaching a peak around 2050, and then gradually decrease. In 2060, the traffic volume of China's civil aviation freight transport will reach 109.45 billion ton-kilometers.

Table 13 Estimated demand for air freight transport (unit = 100 million ton-kilometers)

Year	2025	2030	2035	2040	2045	2050	2055	2060
Freight transport	455.0	650.2	840.2	1021.1	1140.2	1174.7	1166.9	1094.5

3.2.2 Carbon emissions constraints

Aviation is the most challenging industry in the transportation sector in terms of achieving near-zero emissions. Previous studies have comprehensively analyzed China's future carbon emissions goals and the development characteristics of various industries in the transportation sector, and proposed future carbon emissions constraints for the transportation sector. Based on the results of studies by the China Academy of Transportation Sciences, the Institute of Climate Change and Sustainable Development of Tsinghua University [99, 100], and other institutions, we set a carbon emissions path for China's civil aviation sub-sector to achieve the goal of carbon neutrality by 2060, as shown in Table 14. Aviation is the most difficult mode of transport in China's transportation sector in terms of decarbonization. There will still be 25.29 million tons of direct carbon emissions in 2060, even though they will be 73.7% lower than those in 2025.

Table 14 Carbon emissions constraints for China's civil aviation sub-sector (unit = 10,000 tons)

Year	2025	2030	2035	2040	2045	2050	2055	2060
Carbon emissions	9634	11610	11296	10663	9356	6248	4863	2529

3.2.3 Percentage of flights by each aircraft model

Given the rise in demand, the proportion of wide-body passenger aircraft is likely to gradually rise. Currently, narrow-body passenger aircraft models, such as the Boeing 737

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series and the Airbus A320 series, continue to dominate fleets. The proportions of total flights undertaken by B737-800, B737-700, and A320 model aircraft have been always high, remaining at around 70% recently. There was little change in the overall proportion of regional passenger flights.

The proportion of flights by wide-body passenger aircraft is gradually increasing, although the change is not yet significant. The short distances and high frequency of domestic flights mean that the economic efficiency of large passenger aircraft is suboptimal. Given that flights by narrow-body passenger aircraft continue to account for a significant proportion of all passenger flights, we assumed that the proportion of flights by various types of aircraft will remain unchanged in the future, which is in line with the verification results in 2018. Narrow-body passenger aircraft continue to dominate the fleet, with wide-body and regional passenger aircraft only undertaking small numbers of domestic flights.

3.3 Scenario design for the future low-carbon development of China's civil aviation sub-sector

In this study, we assumed that under the baseline scenario, only one technology, biomass fuel, is used to assist in the de-carbonization of the civil aviation sub-sector. In addition to the baseline scenario, we analyzed three alternative scenarios: the comprehensive emissions reduction scenario, the disruptive technology scenario, and the high-speed rail development scenario. The description and design of each scenario is presented in Table 15.

Table 15 Scenario design for the future low-carbon development of China's civil aviation sub-sector

Scenario setting	Scenario description	Retrofit technology	Operational management technology	Disruptive technology
Baseline scenario	Only biomass fuel is used as an alternative fuel technology.	Ignored	Ignored	Ignored
Comprehensive emission reduction scenario	Compared with the baseline scenario, the aircraft that adopts the alternative fuel technology becomes the purchase option of the fleet and the fleet may choose the retrofit technology and management technology.	Considered	Considered	Ignored
Disruptive technology scenario	Compared with the comprehensive emission	Considered	Considered	Considered

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	reduction scenario, the advent of the disruptive aircraft structure and engine technology and their application to commercial use in 2035 is considered.			
Alternative high-speed rail scenario	The impact of China's high-speed rail development plan on the number of flights at each flight distance is considered based on the comprehensive emission reduction scenario.	Considered	Considered	Ignored

Under the comprehensive emissions reduction scenario, retrofitting technology is introduced to aging fleets, which can also apply new operational management technology in an effort to increase the fleet's energy efficiency. Compared with the baseline scenario, the comprehensive emissions reduction scenario takes into account the combined effect of retrofitting, operational management technology, and alternative fuel technology. Compared with the comprehensive emissions reduction scenario, the disruptive technology scenario further considers the possibility of structural changes to aircraft. For example, in 2035, aircraft with blended wings and a propeller fan engine will be available as a purchase option.

The high-speed rail substitution scenario is mainly based on the comprehensive emissions reduction scenario. Given that the number of flights to and from cities with a population of 500,000 will decrease after they obtain access to high-speed rail transport, the relevant decision changes in the development path of civil aviation are explored. The substitution effect of high-speed rail in relation to air transport varies with distance. Based on the results obtained in the previous section, the substitution effect on flights of various distances is shown in Table 16. Overall, after cities with a population of 500,000 obtain access to high-speed rail in 2035, the total number of flights is expected to decrease by about 20%. Because the high-speed rail construction plan beyond 2035 has not been announced, the effect of high-speed rail after 2035 is not considered.

Table 16 Substitution effect of high-speed rail in relation to air transport

High-speed rail operation time range	0~4h	4~6h	6~8h	8~10h	>10h
Substitution effect	75%	42%	13%	11%	6%

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Chapter 4 Results and Discussion

4.1 Key Results

4.1.1 Fleet composition

4.1.1.1 Narrow-body passenger aircraft fleet

Because no alternative fuel technology for passenger aircraft is introduced under the baseline scenario, the total number of flights by traditional narrow-body passenger aircraft will continue to increase, while the number of new-generation passenger aircraft will gradually increase after these aircraft are introduced. The total number of flights by narrow-body passenger aircraft in 2020 was 2,936, and this is estimated to increase to 8,014 in 2060.

During the period from 2020 to 2033, the narrow-body passenger aircraft fleet will mainly consist of previous-generation aircraft models. The results of the fleet optimization decision-making process indicate that old-fashioned aircraft will not be commissioned before 2033. The current-generation aircraft models that commenced operation between 2015 and 2020 will gradually account for a greater proportion of the fleet, eventually accounting for 47.9% of the fleet before the next-generation models start to be commissioned in 2035. With the entry of the next-generation models into service, the number of decommissioned aircraft will gradually increase and previous-generation aircraft models will gradually leave the fleet. Thus, the proportion of next-generation aircraft models in the fleet will increase from 6.1% in 2035 to 51.0% in 2060. In 2044, the airlines will start to purchase hydrogen-powered aircraft to reduce emissions, and by 2060 it is estimated that there will be 3,087 hydrogen-powered aircraft in the narrow-body passenger aircraft fleet. In the short term, current-generation aircraft models will continue to be the mainstay of the fleet, while in the long term, next-generation aircraft models and hydrogen-powered aircraft will become the mainstay of the fleet. In 2060, the fleet will be dominated by hydrogen-powered aircraft and next-generation passenger aircraft, with current-generation aircraft models, hydrogen-powered aircraft, and next-generation aircraft models accounting for 10.5%, 38.5%, and 51.0%, respectively, of the overall fleet, with all previous-generation aircraft models having been decommissioned by then.

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Under the disruptive technology scenario, the adoption of alternative fuel technology aircraft becomes a less economically effective emissions reduction choice because there is no additionally fixed investment and low purchase cost involved in the disruptive technology. After alternative fuel technology aircraft commence operation in 2035, previous-generation aircraft will gradually be decommissioned. In 2060, current-generation aircraft models, hydrogen-powered aircraft, and disruptive technology aircraft will account for 21.3%, 1.2%, and 77.5%, respectively, of the total fleet, while the number of hydrogen-powered aircraft will decline significantly to less than 100 in 2060.

Under the high-speed rail substitution scenario, the total number of passenger aircraft in the fleet will decrease slightly to 6,681 in 2060. Because of the decline in demand, it will be less economical to take fleet measures and the fleet will prefer to combine fuel aircraft with biomass fuel applications to achieve the goal of near-zero emissions. The number of hydrogen-powered aircraft will decrease slightly compared with that under the comprehensive emissions reduction scenario, reaching 1,823 in 2060, and the initial purchase of hydrogen-powered aircraft will be postponed by 3 years. In 2060, current-generation aircraft models, hydrogen-powered aircraft, and next-generation aircraft models will account for 8.3%, 27.3%, and 64.4%, respectively, of the overall fleet, with all previous-generation aircraft having been decommissioned by then. Based on the composition of the narrow-body passenger aircraft fleet under the disruptive technology scenario and the high-speed rail substitution scenario, it can be seen that the number of hydrogen-powered aircraft will fall significantly when either the demand for flights declines or hydrogen-powered aircraft are uneconomical. Thus, reducing demand and improving the economic efficiency of other emissions reduction technologies will help to reduce reliance on emerging alternative fuel technologies.

4.1.1.2 Wide-body passenger aircraft fleet

Under the baseline scenario, the number of wide-body passenger aircraft in the traditional fleet will continue to increase, similar to narrow-body passenger aircraft. In 2020, the total number of wide-body passenger aircraft in the fleet was 410, and this is estimated to increase to 1,060 by 2060.

Because of the low demand for wide-body passenger aircraft, hydrogen-powered aircraft will be introduced relatively late, for example, under the comprehensive emissions reduction scenario, hydrogen-powered aircraft will only start to be purchased

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in 2047. In 2035, next-generation aircraft models will gradually start to be commissioned and previous-generation, current-generation, and next-generation aircraft models will account for 40.4%, 57.6%, and 2.0%, respectively, of the total fleet. After hydrogen-powered aircraft are introduced in 2047, previous-generation aircraft models will gradually be decommissioned, and thus at that point, previous-generation aircraft models, current-generation aircraft models, hydrogen-powered aircraft, and next-generation aircraft models will account for 4.6%, 45.3%, 3.3%, and 46.8%, respectively, of the total fleet. In 2060, it is estimated that there will be 220 hydrogen-powered aircraft in the wide-body passenger aircraft fleet, with next-generation aircraft models, hydrogen-powered aircraft, and current-generation aircraft models accounting for 68.5%, 20.8%, and 10.7%, respectively, of the total fleet.

Under the disruptive technology scenario, similar to narrow-body passenger aircraft, it is not economical to introduce hydrogen-powered aircraft, and thus airlines will tend to choose traditional fuel-powered aircraft with disruptive structures in an effort to reduce emissions. The numbers of aircraft in the fleet that are decommissioned will gradually increase after new aircraft with disruptive structures are introduced. In 2035, previous-generation, current-generation, and disruptive aircraft models will account for 40.4%, 57.6%, and 2.0%, respectively, of the total fleet, and by 2060, current-generation aircraft models, hydrogen-powered aircraft, and disruptive aircraft models will account for 10.6%, 3.2%, and 86.2%, respectively, of the total fleet. It is estimated that there will be 34 hydrogen-powered aircraft in 2060.

Under the high-speed rail development scenario, the total number of passenger aircraft in the fleet will decline, and the number of flights by wide-body passenger aircraft will be less than that by narrow-body passenger aircraft, making it less feasible to adopt fleet-related measures in an attempt to reduce carbon emissions. Furthermore, airlines will tend to use traditional fuel-powered aircraft in an effort to achieve the goal of near-zero emissions. The initial purchase of hydrogen-powered aircraft will be postponed until 2054, after which it is estimated that 47 hydrogen-powered aircraft will be purchased. In 2060, current-generation aircraft models, hydrogen-powered aircraft, and next-generation aircraft models will account for 7.9%, 5.6%, and 86.5%, respectively, of the total fleet, with all previous-generation aircraft models having been decommissioned.

4.1.1.3 Regional passenger aircraft fleet

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Under the baseline scenario, the total number of aircraft in the regional passenger aircraft fleet will continue to increase from 182 in 2020 to 541 in 2060.

In the regional passenger aircraft fleet, electric-powered aircraft will be a more economical option in terms of emissions reduction than hydrogen-powered aircraft, which will only become a purchase option when the hydrogen price falls sufficiently. Under the comprehensive emissions reduction scenario, the initial purchase of electric-powered aircraft will occur in 2047 and that of hydrogen-powered aircraft will occur in 2054. Next-generation aircraft models will gradually be introduced from 2035, at which point previous-generation, current-generation, and next-generation aircraft models will account for 45.3%, 52.2%, and 2.5%, respectively, of the total fleet. In 2047, when electric-powered aircraft are introduced, previous-generation aircraft models will gradually be decommissioned, and previous-generation aircraft models, current-generation aircraft models, electric-powered aircraft, and next-generation aircraft models will account for 4.1%, 42.9%, 4.3%, and 48.7%, respectively, of the total fleet. In 2054, current-generation aircraft models, electric-powered aircraft, hydrogen-powered aircraft, and next-generation aircraft models will account for 30.2%, 46.0%, 0.6%, and 23.2%, respectively, of the total fleet, with all previous-generation aircraft having been decommissioned. In 2060, it is estimated that there will be 185 electric-powered aircraft and 35 hydrogen-powered aircraft in the regional passenger aircraft fleet. The regional passenger aircraft fleet will use electric-powered aircraft as the main alternative fuel technology and include a small number of hydrogen-powered aircraft to aid carbon emissions reduction.

Under the disruptive technology scenario, airlines will tend to choose traditional fuel-powered aircraft with disruptive structures to reduce emissions because there is less need for hydrogen-powered aircraft and electric-powered aircraft, and these types of aircraft are not economical. Thus, airlines will no longer purchase electric-powered and hydrogen-powered aircraft, and the proportion of disruptive technology aircraft in the regional passenger aircraft fleet will be higher than that in the wide-body passenger aircraft fleet and the narrow-body passenger aircraft fleet. In 2060, current-generation aircraft models and disruptive technology aircraft will account for 10.6% and 89.4%, respectively, of the total fleet.

Under the high-speed rail substitution scenario, the initial purchase of electric-powered aircraft will be postponed until 2051, with 116 aircraft being purchased. In 2060,

current-generation aircraft models, electric-powered aircraft, hydrogen-powered aircraft, and next-generation aircraft models will account for 11.4%, 3.2%, 28.8%, and 56.6%, respectively, of the total fleet, with all previous-generation aircraft having been decommissioned.

4.1.2 Carbon emissions

Under the baseline scenario, the overall reduction in emissions is attributable to the use of biomass fuel because this is the only alternative fuel that is available. In 2035, 2050, and 2060, the reduction in carbon emissions as a result of the use of biomass fuel will be 36.751 million tons, 128.941 million tons, and 165.928 million tons, respectively, while demand for biomass fuel will be 12.165 million tons, 42.682 million tons, and 54.926 million tons, respectively.

It can be seen that in 2060, carbon emissions will be 1.58 times those in 2030. Prior to 2030, retrofitting technology and operational management technology are expected to play a vital role in annual emissions reductions of about 10 million tons. Despite the increase in carbon emissions from the civil aviation sub-sector and the tightening of carbon emissions regulations, the effects of retrofitting technologies and operational management technologies will tend to be insignificant, and by 2060, their contribution to total emissions reduction is estimated to be only 6.9%. From 2032, the civil aviation sub-sector will start to use biomass fuel, and thus the contribution of this fuel to total emissions reduction will increase from 10.3% in 2032 to 30.5% in 2060. By 2060, the amount of emissions reduced by the use of biomass fuel is estimated to be 50.674 million tons, an average annual growth rate in terms of emissions reduction of 11.2%. The contribution of hydrogen-powered aircraft to emissions reduction will gradually increase as the numbers of hydrogen-powered aircraft in the narrow-body passenger aircraft fleet and the wide-body passenger aircraft fleet increase. The reduction in emissions as a result of using hydrogen-powered aircraft is estimated to reach 464,000 tons in 2044 and 57.674 million tons in 2060, an average annual growth rate in terms of emissions reduction of 35.1%. The introduction of next-generation aircraft models will also significantly reduce carbon emissions, with the reduction in emissions estimated to be 3.002 million tons in 2035, when they are introduced, increasing to 40.432 million tons in 2060. The small number of electric-powered aircraft and the small number of passengers they are expected to carry mean that they will only make a small contribution to carbon emissions reduction.

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Overall, in the short term, the introduction of retrofitting technology, operational management technology, and biomass fuel will be used as the main emissions reduction measures. In the long term, given the expected reduction in hydrogen prices, next-generation aircraft models and hydrogen-powered aircraft will become the main measures used in an attempt to achieve the goal of near-zero emissions. The contributions of retrofitting technologies and operational management technologies to total emissions reduction will exceed 50% before 2031. After 2050, the contribution of hydrogen-powered aircraft to emissions reduction will exceed 10%, while that of next-generation aircraft models and biomass fuel will remain at around 30%.

Compared with the comprehensive emissions reduction scenario, the disruptive technology scenario sees a reduced demand for alternative fuel-powered aircraft as airlines turn to traditional fuel passenger aircraft for emissions reduction. In 2060, the reduction in emissions as a result of the use of hydrogen-powered aircraft will be 3.267 million tons, or 93.6% less than that under the comprehensive emissions reduction scenario. The contribution of disruptive technology to emissions reduction is expected to increase rapidly after its introduction in 2035. In 2040, 2050, and 2060, the reduction in emissions as a result of the use of this technology is estimated to be 23.439 million tons, 59.539 million tons, and 76.427 million tons, respectively. The use of biomass fuel does not require equipment updates. After alternative fuel technology aircraft are introduced, their contribution to emissions reduction in 2040, 2050, and 2060 is estimated to be 17.881 million tons, 45.027 million tons, and 69.497 million tons, respectively. In 2060, the contributions of retrofitting technology, operational management technology, biomass fuel, hydrogen-powered aircraft, and disruptive technology aircraft to total emissions reduction are estimated to be 7.1%, 42.1%, 2.0%, 2,5% and 46.3%, respectively. The disruptive technology scenario indicates that innovations in relation to traditional fuel passenger aircraft can help to achieve the goal of near-zero emissions and reduce the pressure arising from the introduction of alternative fuel-powered aircraft. Meanwhile, the introduction of disruptive technology aircraft might increase the use of biomass fuel, thereby increasing pressure on biomass aviation fuel supply. Thus, disruptive technology applied to traditional aircraft is most effective when it is combined with the use of biomass fuel.

The introduction of high-speed rail will postpone the introduction of biomass fuel, hydrogen-powered aircraft, and electric-powered aircraft, until 2037, 2046, and 2053,

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respectively. In 2060, next-generation aircraft models and biomass fuel will account for 34.6% and 29.1% of total emissions reductions, respectively. The introduction of high-speed rail will reduce the reliance of the civil aviation sub-sector on alternative fuel technology for emissions reduction, and hydrogen-powered aircraft will account for 27.8% of the total reduction in emissions.

Because of a lack of flight data regarding freight transport, in this study, we used the freight traffic volume, energy consumption factor, and emissions factor to calculate the energy consumption and carbon emissions of air freight transport. We assumed that air freight fleets used biomass fuel in an effort to reduce carbon emissions. In 2035, 2050, and 2060, carbon emissions from air freight transport are estimated to be 16.868 million tons, 19.049 million tons, and 8.688 million tons, respectively, with emissions gradually falling after 2040 at an average annual rate of 4.0%.

4.1.3 Emissions reduction costs in China's civil aviation sub-sector

Compared with the baseline scenario, the other scenarios all show a slight decrease in emissions reduction costs. It can be seen that total operating costs under the comprehensive emissions reduction scenario are 33.44 billion US dollars less than those under the baseline scenario. The application of retrofitting technology and alternative fuel technology enable a significant drop in operating costs under the comprehensive emissions reduction scenario. Accelerated fleet updates will also increase residual value recovery and reduce purchase and decommissioning costs, which are estimated to fall by 7.81 billion US dollars and 36.76 billion US dollars, respectively. Both retrofitting technology and operational management technology have a dual effect, reducing both costs and carbon emissions. In summary, total operating costs under the comprehensive emissions reduction scenario will decrease by 2.9% compared with those under the baseline scenario.

Under the disruptive technology scenario, operating costs will further increase, to 1119.38 billion US dollars, an additional decrease of 1.7% compared with those under the comprehensive emissions reduction scenario. Because of the slight increase in the purchase costs of aircraft with disruptive structures, the purchase and decommissioning costs of the fleet will slightly increase and the operating costs in relation to fuel will drop by 10.82 billion US dollars.

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Under the high-speed rail substitution scenario, the decrease in demand will result in a significant decline in total operating costs. Various costs will drop by 10% to 20% compared with those under the comprehensive emissions reduction scenario, with total operating costs estimated to be 943.13 billion US dollars.

In terms of emissions reduction costs, during the period from 2020 to 2060, all scenarios will see a total of 3.03 billion tons of emissions cut under the low-carbon development path and 2.13 billion tons of emissions will be reduced under the high-speed rail substitution scenario. Given the increased energy efficiency of new aircraft models, the emissions reduction costs under the baseline scenario, comprehensive emissions reduction scenario, disruptive technology scenario, and high-speed rail scenario will be 306.95 billion US dollars, 273.5 billion US dollars, 254.16 billion US dollars, and 77.91 billion US dollars, respectively, or 101.3 US dollars, 90.3 US dollars, 83.9 US dollars, and 94.2 US dollars per ton, respectively. Based on the emissions reduction costs under each scenario, although total emissions reduction costs will fall as a result of reduced demand under the high-speed rail substitution scenario, the emissions reduction costs under this scenario will be higher than those under the comprehensive emissions reduction scenario because of the failure to utilize the economic efficiency of hydrogen-powered aircraft in later years.

The purchase and decommissioning costs under each scenario are shown in Table 17.

Table 17 Purchase and decommissioning costs (unit = 100 million US dollars)

		Comprehensive emission reduction scenario	Disruptive technology scenario	High-speed rail substitution scenario
Active decommissioning	Narrow-body passenger aircraft	-62.3	-65.3	-63
	Wide-body passenger aircraft	-11.4	-13.6	-13.6
	Regional passenger aircraft	-1.4	-2.1	-7.6
Purchase of current-generation aircraft models	Narrow-body passenger aircraft	1869.6	1866.3	1340.3
	Wide-body passenger aircraft	900	900	592

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	Regional passenger aircraft	67.7	67.7	49.1
Purchase of next-generation aircraft models	Narrow-body passenger aircraft	1143.3	1460.2	1140.6
	Wide-body passenger aircraft	374.7	434	365
	Regional passenger aircraft	33.6	49	32.3
Purchase of hydrogen-powered aircraft	Narrow-body passenger aircraft	298.3	12	158.9
	Wide-body passenger aircraft	77.8	6.1	9.1
	Regional passenger aircraft	0.8	0	1.5
Purchase of electric aircraft	Narrow-body passenger aircraft	0	0	0
	Wide-body passenger aircraft	0	0	0
	Regional passenger aircraft	10.2	0	4.9

Fleet purchase and decommissioning costs are mainly incurred in relation to current-generation aircraft models. Decommissioning, electric-powered aircraft purchases, and hydrogen-powered aircraft purchases account for relatively low proportions of total costs. Under the comprehensive emissions reduction scenario, the purchase costs of current-generation aircraft models, next-generation aircraft models, and hydrogen-powered aircraft account for 60.3%, 33.0%, and 8.0%, respectively, of the total purchase and decommissioning costs. Narrow-body passenger aircraft account for the highest proportion of the total costs, reaching 70% under each scenario.

4.2 Sensitivity Analysis

Changes in the price of hydrogen, the speed of development of alternative fuel technologies, and the range of improvements in the energy efficiency of traditional fuel-powered aircraft all have a significant effect on decision-making in relation to the passenger transport fleet. In this subsection, we conduct a sensitivity analysis of key

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parameters such as the hydrogen price, the time of introduction of hydrogen-powered aircraft, and the degree of improvement in the energy efficiency of next-generation aircraft models, and explore the effect of changes in key indicators on the optimal path toward near-zero carbon emissions in the civil aviation sub-sector.

4.2.1 Hydrogen price

The price of liquid hydrogen fuel will gradually decrease with the expansion of the hydrogen fuel industry, and will determine the relative economic efficiency of hydrogen-powered aircraft. Based on the high-speed rail substitution scenario, in this study, we consider significant changes in the hydrogen price to determine the optimal decision-making for the civil aviation sub-sector under the scenario of rapid development and use of hydrogen fuel. The changes in the hydrogen price we used in this study, which were based on the results of previous studies on the likely hydrogen price under various scenarios [84-86, 88]. Scenario H0 corresponds to the high-speed rail substitution scenario, whereby the hydrogen price will eventually fall to 10 yuan per kg in 2060. Under scenarios H1 and H2, increases in the capacity of the electro bath, the optimization of manufacturing materials, and declines in the electricity price mean that the hydrogen price will fall more quickly, to about 10 yuan/kg in 2045 under both scenarios, and to 7 yuan/kg and 5 yuan/kg, respectively, in 2060.

Lower hydrogen prices make hydrogen-powered aircraft a more attractive purchase option for airlines seeking to reduce emissions. Hydrogen-powered aircraft are expected to be introduced before 2045, but might be introduced earlier if the price of hydrogen falls sufficiently. The number of hydrogen-powered aircraft will also increase significantly, reflecting the improved economic efficiency of hydrogen-powered aircraft when hydrogen fuel production increases. The hydrogen price will further decrease; the purchase volume of hydrogen-powered aircraft for civil aviation transport will further increase; alternative fuels and traditional fuels can make a contribution to carbon reduction. The regional passenger aircraft fleet will begin to purchase mainly hydrogen-powered aircraft after 2055. Under the three hydrogen price scenarios, namely H0, H1, and H2, the number of hydrogen-powered aircraft that are purchased in 2060 is estimated to be 1,883, 4,952, and 5,330, respectively. It is assumed that as the hydrogen price continues to fall, the number of hydrogen-powered aircraft will increase by 3.7 times and 4.0 times in 2055 and 2.6 times and 2.8 times in 2060. Thus, the hydrogen price will affect

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the economic efficiency of hydrogen-powered aircraft. If the hydrogen price is sufficiently low, updating the fleet with hydrogen-powered aircraft will become a more economical option in terms of emissions reduction.

Further reductions in the hydrogen price will reduce overall fleet operating costs accordingly. Under the three hydrogen price scenarios, namely H0, H1, and H2, total operating costs will be 943.7 billion US dollars, 938.4 billion US dollars, and 936.19 billion US dollars, respectively, that is, total operating costs under scenarios H1 and H2 will be 0.5% and 0.8% lower, respectively, than those under scenario H0. If aircraft purchase costs and fleet operating costs are taken into account, scenarios H1 and H2 will reduce the costs of emissions reduction by 2.4% and 3.5%, respectively. Although the fall in the hydrogen price reduces the overall emissions reduction costs, it also enables hydrogen-powered aircraft to be commissioned earlier. Thus, to achieve the optimal emissions reduction path, the scale of hydrogen production and the development of hydrogen-powered aircraft must be coordinated. If hydrogen-powered aircraft can be commissioned earlier, it is necessary to match the introduction of the aircraft with low hydrogen prices to give full play to the emissions reduction advantages offered by this technology.

4.2.2 Introduction of hydrogen-powered aircraft

A delay in the introduction of hydrogen-powered aircraft will increase overall emissions reduction costs, and the increased economic efficiency as a result of reductions in the hydrogen price will not be achieved. The number of hydrogen-powered aircraft that are expected to be purchased if the introduction of hydrogen-powered aircraft is postponed until 2050, based on the high-speed rail substitution scenario. A delay in the commissioning of hydrogen-powered aircraft will accelerate the commissioning of hydrogen-powered aircraft once they are eventually introduced. A total of 2,888 hydrogen-powered aircraft will be purchased by 2060, including 5.4% more aircraft than will be commissioned by 2040. A large number of aircraft will be decommissioned after 2050, and the introduction of hydrogen-powered aircraft that year will increase emissions reduction costs by 2.3%.

Thus, it can be seen that a delay in the commissioning of hydrogen-powered aircraft has two adverse effects. First, a delay in commissioning will make the period during

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which hydrogen-powered aircraft are introduced into the fleet shorter and more intensive, creating pressure in relation to fleet substitution. If hydrogen-powered aircraft are commissioned from 2050, the number of aircraft decommissioned after 2050 will increase by 11.2% compared with the number if hydrogen-powered aircraft are commissioned from 2040. Second, total emissions reduction costs will increase, mainly because of the additional purchase of hydrogen-powered aircraft in an effort to achieve the short-term emissions reduction goal during the period from 2050 to 2060. Thus, total purchase costs will increase accordingly.

4.2.3 Energy efficiency of next-generation aircraft models

The increased energy efficiency of next-generation passenger aircraft will directly affect emissions reduction costs by reducing reliance on biomass fuel and hydrogen-powered aircraft for the low-carbon development of the civil aviation sub-sector. Thus, in this subsection, we analyze the uncertainty of the key influencing factor of energy efficiency improvement percentage of next-generation and current-generation aircraft models.

Based on the high-speed rail substitution scenario, we assume that there are four scenarios, E0, E1, E2, and E3, under which the energy efficiency of next-generation aircraft models increases by 15%, 20%, 25%, and 30%, respectively, compared with that of current-generation aircraft models. Energy efficiency improvements in traditional fuel-powered aircraft will significantly improve their economic efficiency, making it uneconomical to introduce hydrogen-powered aircraft. Thus, the number of hydrogen-powered aircraft purchased under scenarios E2 and E3 will be 71.2% and 99.0%, respectively, less than that under scenario E1. The results show that when the energy efficiency of next-generation passenger aircraft models is 30% higher than that of current-generation passenger aircraft models, hydrogen-powered aircraft are not an economical alternative, and the optimal path for the low-carbon development of the fleet is to introduce next-generation aircraft models and adopt biomass fuel to achieve the goal of near-zero emissions.

In scenarios where the efficiency improvements of next-generation aircraft models fail to meet expectations, hydrogen-powered aircraft will be commissioned earlier. Under scenario E0, the number of hydrogen-powered aircraft purchased will be 18.0% greater than that under scenario E1, and they will be commissioned 5 years earlier.

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Next-generation aircraft models are expected to be introduced from 2035 to 2040. In terms of the goal of near-zero emissions in 2060, next-generation aircraft models will play a key transitional role in the medium term before hydrogen production reaches the necessary scale for hydrogen-powered aircraft to be economical. Further breakthroughs in energy efficiency will also reduce the demand for alternative fuels. In terms of total emissions reduction costs, the premature commissioning of hydrogen-powered aircraft is not a good option. During the period from 2035 to 2050, the decline in the hydrogen price will be insufficient to enable hydrogen-powered aircraft to deliver the necessary economic efficiency. Thus, premature commissioning of hydrogen-powered aircraft will increase total emissions reduction costs, which will be 5.9% greater under scenario E0 than under scenario E1. The cost of carbon dioxide emissions will be 99.8 US dollars per ton.

Thus, we believe that the increased energy efficiency of next-generation aircraft models will determine the substitution path and emissions reduction costs of the civil aviation sub-sector. If the increase in energy efficiency of next-generation aircraft models is insufficient, hydrogen-powered aircraft will be introduced earlier, increasing total emissions reduction costs.

Chapter 5 Conclusions and Suggestions

5.1 Conclusions

Using a fleet optimization model and historical flight data for China, in combination with factors such as changes in demand, retrofitting technology, operational management technology, alternative fuels, energy efficiency improvements, and disruptive technology, in this study, we identify the optimal path for the development of China’s civil aviation sub-sector from a fleet perspective toward the goal of near-zero emissions in 2060.

It is found that a combination of retrofitting technology, operational management technology, alternative fuel technology, and energy efficiency improvements will facilitate the optimal low-carbon development path of the civil aviation sub-sector by exploiting the availability of biomass fuel in the short term and the emissions reduction potential of hydrogen fuel and the development of China’s high-speed rail network in the medium and long terms to reduce emissions reduction costs.

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(1) A combination of various low-carbon technologies will optimize the development path of the civil aviation sub-sector. The combined use of retrofitting technology, operational management technology, and alternative fuel technology, together with improvements in energy efficiency, will reduce the costs of achieving the goal of near-zero emissions by 2060 by 10.9% compared with the use of biomass fuel alone. Under the optimal development path, hydrogen-powered aircraft will be introduced in 2046, and by 2060, the fleet will be dominated by fuel cell aircraft and next-generation aircraft. Current-generation aircraft models, hydrogen-powered aircraft, and next-generation aircraft models will account for 10.5%, 38.5%, and 51.0%, respectively, of the total fleet, and previous-generation aircraft models will be completely decommissioned. In 2060, biomass fuel and hydrogen will account for 30.5% and 34.4%, respectively, of the contribution of alternative fuels to emissions reduction. Because of their limited battery life, electric-powered aircraft will not be in widespread use, and thus will only make a small contribution to emissions reduction.

(2) If a disruptive airframe technology emerges, emissions reduction costs will be further reduced and the demand for alternative fuels will decline. The introduction of hydrogen-powered aircraft to the narrow-body passenger aircraft fleet will be delayed till around 2051 and the number will be greatly reduced, indicating that the pursuit of improvements in traditional aircraft is the most economical carbon reduction measure. Total emissions reduction costs will be lowest under the disruptive technology scenario, at 83.9 US dollars per ton of carbon dioxide.

(3) The introduction of high-speed rail will accelerate the decarbonization of the civil aviation sub-sector and ease the need to introduce alternative fuels. Under the high-speed rail substitution scenario, the introduction of biomass fuel and hydrogen-powered aircraft will be delayed until 2037 and 2046, respectively, because the reduced demand will make fleet substitution uneconomical. The introduction of high-speed rail will reduce the reliance of the civil aviation sub-sector on alternative fuel technology along its path to de-carbonization, and by 2060, the contribution of hydrogen-powered aircraft to emissions reduction will fall to 27.8%.

(4) The hydrogen price will significantly affect the emissions reduction costs of the civil aviation sub-sector by determining the economic efficiency of hydrogen-powered aircraft. If the hydrogen price can be reduced to 7 RMB/kg or 5 RMB/kg by 2060, the

hydrogen-powered aircraft fleet will increase by 2.6 times or 2.8 times, respectively, and total emissions reduction costs will fall by 0.5% or 0.8%, respectively.

(5) The delay in the commissioning of hydrogen-powered aircraft will delay the realization of the economic benefits of hydrogen-powered aircraft in the later development stages of the civil aviation sub-sector, and might also lead to an increase in the annual number of hydrogen-powered aircraft that are purchased in the later stages. Furthermore, the commissioning of hydrogen-powered aircraft will increase the pressure on fleet substitution. If hydrogen-powered aircraft are commissioned in 2050, total emissions reduction costs will increase by 2.3% compared with when they are commissioned in 2040.

5.2 Policy Suggestions

A combination of multiple low-carbon technologies should be used to facilitate the de-carbonization of the civil aviation sub-sector. It is also necessary to accelerate the development of the high-speed rail network and promote the transfer of the transport load from aviation to more economical transportation modes. Meanwhile, retrofitting technology, operational management technology, alternative fuel technology, and inter-generational improvements in energy efficiency should be combined to promote the de-carbonization of the civil aviation sub-sector. In the short term, the focus should be on the application of retrofitting technology and operational management technology, the use of biomass fuel should gradually increase in the medium term, and the economic efficiency of hydrogen-powered aircraft when the hydrogen price falls sufficiently should be exploited in the long term.

Key References

[1]. WANG Hailin, HE Jiankun. Peaking rule of CO_2 emissions, energy consumption and transport volume in transportation sector [J]. China Population Resources and Environment, 2018, 28(02): 59-65.

[2]. FU Zhihuan, SUN Yongfu, WENG Mengyong, et al. Strategic Research on Transportation Power [M]. Beijing: China Communications Press, 2019.

[3]. Civil Aviation Administration of China. Statistical Bulletin on the Development of China's Civil Aviation Industry 2019 [R]. Beijing: Civil Aviation Administration of China, 2020.

[4]. Civil Aviation Administration of China. Notice of the Civil Aviation Administration of China on issuing the

outline of the action plan for building a powerful in the civil aviation industry for a new era [EB/OL]. [2019-2-19]. http://www.caac.gov.cn/XXGK/XXGK/ZFGW/201812/t20181212_193447.html.

[5]. WANG Hailin. Model simulation of China's low-Carbon transport transformation mechanisms and policies [D]. Beijing: Tsinghua University, 2016.

[6]. Civil Aviation Administration of China. Thirteenth five-year plan for the energy conservation and emission reduction of civil aviation [EB/OL]. [2021-2-16]. http://www.caac.gov.cn/XXGK/XXGK/FZGH/201704/P020170405613883028466.pdf.

[7]. International Civil Aviation Organization. State Action Plans, and Assistance [EB/OL]. [2021-1-15]. https://www.icao.int/environmental-protection/Pages/ClimateChange_ActionPlan.aspx.

[8]. Dray L M, Krammer P, Doyme K, et al. AIM2015: Validation and initial results from an open-source aviation systems model[J]. Transport Policy, 2019,79: 93-102.

[9]. Owen B, Lee D S, Lim L. Flying into the Future: Aviation Emissions Scenarios to 2050[J]. Environmental Science & Technology, 2010,44(7): 2255-2260.

[10]. Gudmundsson S V, Anger A. Global carbon dioxide emissions scenarios for aviation derived from IPCC storylines: A meta-analysis[J]. Transportation research. Part D, Transport and environment, 2012,17(1): 61-65.

[11]. Carlsson F, Hammar H. Incentive-based regulation of CO_2 emissions from international aviation[J]. Journal of air transport management, 2002,8(6): 365-372.

[12]. Macintosh A, Wallace L. International aviation emissions to 2025: Can emissions be stabilised without restricting demand?[J]. Energy Policy, 2009,37(1): 264-273.

[13]. Kieckhäfer K, Quante G, Müller C, et al. Simulation-based analysis of the potential of alternative fuels towards reducing CO_2emissions from aviation[J]. Energies, 2018,11(1): 186.

[14]. Loo B P Y, Li L. Carbon dioxide emissions from passenger transport in China since 1949: Implications for developing sustainable transport[J]. Energy Policy, 2012,50: 464-476.

[15]. Zhou W, Wang T, Yu Y, et al. Scenario analysis of CO_2 emissions from China's civil aviation industry through 2030[J]. Applied Energy, 2016,175: 100-108.

[16]. Pan X, Wang H, Wang L, et al. Decarbonization of China's transportation sector: In light of national mitigation toward the Paris Agreement goals[J]. Energy, 2018,155: 853-864.

[17]. International Council on CleanTransportation. Global transportation energy and climate roadmap[R]. Washington DC: ICCT, 2012.

[18]. CAI Bofeng, CAO Dong, LIU Lancui, et al. Research on CO_2 emissions from transportation in China [J]. Climate Change Research, 2011, 7 (03): 197-203.

[19]. International Civil Aviation Organization. ICAO Carbon Emissions Calculator Methodology[R]. Montreal, Canada: ICAO, 2016.

[20]. International Civil Aviation Organization. Mannual on Air Traffic Forecasting[R]. Montreal, Canada: ICAO, 2006.

[21]. Wang H, Ou X, Zhang X. Mode, technology, energy consumption, and resulting CO_2 emissions in China's transport sector up to 2050[J]. Energy Policy, 2017,109: 719-733.

[22]. HE Jicheng. Dynamic change in ecological footprint of energy consumption of aircraft in China during recent 50

years [J]. Ecological Science, 2016, 35(01): 189-193.

[23]. Schäfer A, Evans A D, Reynolds T G, et al. Costs of mitigating CO_2 emissions from passenger aircraft[J]. Nature Climate Change, 2016,6(4): 412-418.

[24]. Schaefer M. Development of a forecast model for global air traffic emissions[D]. Koln: Deutsches Zentrum für Luft- und Raumfahrt, 2012.

[25]. Rosskopf M, Lehner S, Gollnick V. Economicenvironmental trade-offs in long-term airline fleet planning[J]. Journal of Air Transport Management, 2014,34: 109-115.

[26]. Müller C, Kieckhäfer K, Spengler T S. The influence of emission thresholds and retrofit options on airline fleet planning: An optimization approach[J]. Energy Policy, 2018,112: 242-257.

[27]. LIU Junling, SUN Yihe, WANG Ke, etc. Study on mid- and long-term low carbon development pathway for China's transport sector [J]. Climate Change Research, 2018, 14(05): 513-521.

[28]. International Air Transport Association. Aircraft technology roadmap to 2050[R]. Montreal, Canada: IATA, 2013.

[29]. Department of Development Planning, Civil Aviation Administration of China. Statistical Data on Civil Aviation of China 2018 [M]. Beijing: China Civil Aviation Publishing House, 2019.

[30]. WANG Qingyi. Energy data 2020 [M]. Beijing: Green Development Institute, 2021.

[31]. SUN Hong, HUANG Ganxiang, WANG Xiaodong. An evaluation model for average fuel consumption of civil passenger aircraft routes [J]. Industrial Engineering, 2014, 17(05): 41-45.

[32]. LIU Jing. An aircraft fuel estimation model based on flight data analysis [D]. Nanjing: Nanjing University of Aeronautics and Astronautics, 2010.

[33]. Dray L M, Schäfer A W, Al Zayat K. The global potential for CO_2emissions reduction from jet engine passenger aircraft[J]. Transportation Research Record: Journal of the Transportation Research Board, 2018,2672(23): 40-51.

[34]. Pagoni I, Psaraki-Kalouptsidi V. Calculation of aircraft fuel consumption and CO_2 emissions based on path profile estimation by clustering and registration[J]. Transportation Research Part D: Transport and Environment, 2017,54: 172-190.

[35]. Burzlaff M. Aircraft Fuel Consumption-Estimation and Visualization[EB/OL]. [2019-8-7]. https://dataverse harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/2HMEHB.

[36]. Aviation Elliott. Fuel Calculator[EB/OL]. [2019-1-9]. https://www.elliottaviation.com/fbo-services/fuel-calculator/.

[37]. BOEING. AERO - Blended winglets improve performance[EB/OL]. [2017-5-3]. https://www.boeing.com/commercial/aeromagazine/articles/qtr_03_09/article_03_1 html.

[38]. AIRBUS. AirAsia to become first Airbus A320 'Sharklets' operator[EB/OL]. [2018-9-2]. https://www.airbus.com/newsroom/press-releases/en/2012/09/airasia-to-become-first-airbus-a320-sharklets-operator html.

[39]. Cansino J M, Román R. Energy efficiency improvements in air traffic: The case of Airbus A320 in Spain[J]. Energy Policy, 2017,101: 109-122.

[40]. Chilton D, De Graaff A, Baalbergen E, et al. Reduced Emissions of Transport aircraft Operations by Fleet wise Implementation of new Technology[R]. Europe: Fokker Services, 2012.

[41]. BOEING Aviation Partners. Program List Prices[EB/OL]. [2018-5-3]. http://www.aviationpartnersboeing.com/products_list_prices.php.

[42]. AIRBUS. Airbus passenger aircraft Family[EB/OL]. [2018-7-6]. https://www.airbus.com/aircraft/passenger-aircraft/a220-family.html.

[43]. BOEING. About the Boeing 737 MAX[EB/OL]. [2018-9-2]. About the Boeing 737 MAX.

[44]. Watterson A, Spafford C, Hunter B, et al. To re-engine or not to re-Engine: that is the question[R].Oliver Wyman, 2010.

[45]. the House Committee on Infrastructure. The design development and certification of the boeing 737 MAX[R]. Boston: HIS, 2020.

[46]. Hospodka J. Cost-benefit analysis of electric taxi systems for aircraft[J]. Journal of Air Transport Management, 2014,39: 81-88.

[47]. Nikoleris T, Gupta G, Kistler M. Detailed estimation of fuel consumption and emissions during aircraft taxi operations at Dallas/Fort Worth International Airport[J]. Transportation Research Part D: Transport and Environment, 2011,16(4): 302-308.

[48]. LI Kaiwei. Research on the performance of aircraft ground taxiing system. Tianjin: Civil Avaition University of China, 2018.

[49]. Wijnterp C, Roling P C, De Wilde W. Electric taxi systems:An operations and value estimation[J]. AIAA-2014, 2014,3266.

[50]. World Bank. Air transport and energy efficiency[R]. Washington D.C.: World Bank, 2012.

[51]. Vera-Morales M, Graham W, Hall C, et al. Techno-Economic Analysis of Aircraft[R]. Cambridge: University of Cambridge, 2008.

[52]. Reynolds T G, Marais K B, Muller D, et al. Evaluation of potential near-term operational changes to mitigate environmental impacts of aviation[C]// 27TH INTERNATIONAL CONGRESS OF THE AERONAUTICAL SCIENCES, 2010.

[53]. LYU Xiaoping. New technology development of air traffic control and China's countermeasures [J]. China Civil Aviation, 2008, 9: 11-14.

[54]. ICAO. Manual on air traffic management system requirements[R]. Montreal: ICAO, 2008.

[55]. Jensen L, Hansman R J, Venuti J C, et al. Commercial Airline Speed Optimization Strategies for Reduced Cruise Fuel Consumption[J]. AIAA 2013, 2013,4289.

[56]. eynolds T G. Analysis of Lateral Flight Inefficiency in Global Air Traffic Management[C]// 8th AIAA Aviation Technology, Integration and Operations Conference, Anchorage, Alaska, 2008.

[57]. Lovegren J A, Hausman R J. Estimation of potential aircraft fuel burnreduction in cruise via speed and altitudeoptimization strategies[R]. Boston: MIT, 2011.

[58]. Guo R, Zhang Y, Wang Q. Comparison of emerging ground propulsion systems for electrified aircraft taxi operations[J]. Transportation Research Part C: Emerging Technologies, 2014,44: 98-109.

[59]. Nakahara A, Reynolds T, White T, et al. Analysis of a Surface Congestion Management Technique at New York JFK Airport[C]// 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Virginia Beach, 2011.

[60]. Mouillet V, Nuic A, Casado E, et al. Evaluation of the applicability of a modern aircraft performance model to trajectory optimization: IEEE, 2018.

[61]. Balakrishnan H, Chandran B. Scheduling aircraft landings under constrained position shifting[C]// AIAA, Colorado, 2006.

[62]. HOU Wentao. Research on the optimization technology of launch rate at large airports [D]. Tianjin: Civil Aviation University of China, 2014.

[63]. YANG Shuangshuang, Zhu Huaqiang. Research on the optimization of aircraft launch decisions [J]. Journal of Wuhan University of Technology (Transportation Science & Engineering), 2014,38(1): 227-231.

[64]. LIU Wenzhi. Life cycle assessment and economical efficiency analysis of jet fuel from biomass gasification and Fischer-Tropsch synthesis [D]. Wuhan: Huazhong University of Science and Technology, 2018.

[65]. Xi Shuai. Technical analysis of biomass preparation of aviation kerosene [J]. Jiangxi Chemical Industry, 2019 (5): 116.

[66]. Xu J, Yuan Z, Chang S. Long-term cost trajectories for biofuels in China projected to 2050[J]. Energy, 2018,160: 452-465.

[67]. Natelson R H, Wang W, Roberts W L, et al. Technoeconomic analysis of jet fuel production from hydrolysis, decarboxylation, and reforming of camelina oil[J]. Biomass and Bioenergy, 2015,75: 23-34.

[68]. Diederichs G W, Ali Mandegari M, Farzad S, et al. Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice[J]. Bioresource Technology, 2016,216: 331-339.

[69]. Gnadt A R. Technical and environmental assessment of all-electric 180-passenger commercial aircraft[D]. Boston: MIT, 2018.

[70]. WSDOT. Electric aircraft working group report[R]. Washington DC: WSDOT, 2019.

[71]. EuropeanCommission. Flightpath2050 Europe's Vision for Aviation[R]. Belgium: EU, 2011.

[72]. Thapa N, Ram S, Kumar S, et al. All electric aircraft: A reality on its way[J]. Materials today: Proceedings, 2021,43: 175-182.

[73]. Forencis Research. Electric aircraft market by type (Light jet, ultra-Light aircraft) by Technology (all Electric, full Hybrid, more electric hybrid) by component (electric motor, battery) by region (North America, Europe, Asia Pacific, Middle East & Africa, South America) – Global Forecast (2019 to 2027)[R]. Washington: FR, 2019.

[74]. Schäfer A W, Barrett S R H, Doyme K, et al. Technological, economic and environmental prospects of all-electric aircraft[J]. Nature Energy, 2019,4: 160-166.

[75]. Ploetner K O. Operating cost estimation for electric-powered transport aircraft: 2013 aviation technology, integration, and operations Conference[C]//2013.

[76]. Mckinsey. Hydrogen-powered aviation, A fact-based study of hydrogen technology, economics and climate impact by 2050[R]. Belgium: Mckinsey, 2020.

[77]. Amy C, Kunycky A. Hydrogen as a renewable energy carrier for commercial aircraft[R]. Cornell: Cornell University, 2019.

[78]. Ahluwalia R K, Cetinbas C F, Peng J K, et al. Total cost of inventory (TCO) analysis of hydrogen fuel cells in aviation preliminary results[R]. Argonne: Argonne National Laboratory, 2020.

[79]. S B, M T, J H, et al. Opportunities for hydrogen in aviation[R].Canberra: CSIRO, 2020.

[80]. Bicer Y, Dincer I. Life cycle evaluation of hydrogen and other potential fuels for aircrafts[J]. International Journal of Hydrogen Energy, 2017, 42(16): 10722-10738.

[81]. Pereira S E R, Fontes T A, C M. Can hydrogen or natural gas be alternatives for aviation e A life cycle assessment[J]. International Journal of hydrogen Energy, 2014, 39: 13266-13275.

[82]. Newsum S. Renewable Energy and Hydrogen in Commercial Aviation[R]. Seatle: Boeing, 2020.

[83]. AirTransportActionGroup. Waypoint 2050[R].Geneva: ATAG, 2020.

[84]. International Energy Agency. The Future of Hydrogen[R]. Paris: IEA, 2019.

[85]. International Renewable Energy Agency. Green hydrogen cost reduction scaling up electrolysers to meet the 1.5 degree climate goal[R]. Bern: IRENA, 2020.

[86]. HydrogenCouncil. Path to hydrogen competitveness A cost perspective[R]. Davos:HydrogenCouncil, 2020.

[87]. China EV100. China Hydrogen Energy Industry Development Report 2020 [R]. Beijing: China EV100, 2020.

[88]. China Hydrogen Alliance. China Hydrogen and Fuel Cell Industry Handbook [R]. Beijing: China Hydrogen Alliance, 2020.

[89]. Dickson N. Setting the scene: Aviation in sector CO_2 emissions reductions: trends and achievements[R]. Montreal: ICAO, 2020.

[90]. TAN Jing, SHI Ruijun, SUN Zhanheng. Research and Development of Pro-fan Engines [J]. Internal Combustion Engine & Parts, 2019, 3: 44-45.

[91]. Van Zante D E. Progress in open rotor research a U.S. perspective[C]// Proceedigns of ASME Turbo Expo 2015, Montreal, Canada, 2015.

[92]. WANG Gang, ZHANG Binqian, ZHANG Minghui, et al. Research progress and prospect for conceptual and aerodynamic technology of blended-wing-body civil aircraft [J]. Acta Aeronautica et Astronautica Sinica, 2019,40(09): 7-35.

[93]. ZHAO Quan. Research on the comprehensive performance of strut-braced wing aircraft. Nanjing: Nanjing University of Aeronautics and Astronautics, 2007.

[94]. GUO Ya-jun, GAO Chao, XIAO Hong, et al. Research on Aerodynamic Characteristics of a Box-wing Configuration [J]. Aeronautical Computing Technique, 2012, 42 (2): 39-41.

[95]. Liebeck R H. Design of the blended wing body subsonic transport[J]. Journal of Aircraft, 2004,41(1): 10-25.

[96]. Guynn M D, Berton J J, Haller W J, et al. Performance and Environmental Assessment of an Advanced Aircraft with Open Rotor Propulsion[R]. Hampton, Virginia: NASA, 2012.

[97]. Airbus. Airbus 2018-2037 market forecast[R]. Toulouse: Airbus, 2019.

[98]. Boeing. Boeing Commercial Market Outlook 2019-2038[R]. Seatle: Boeing, 2019.

[99]. OU Xunmin, YUAN Zhiyi, OUYANG Bin, et al. Final Energy Consumption and CO_2 Emissions of China's Transportation Sector [R]. Beijing: Tsinghua University, 2020.

[100]. The Institute of Climate Change and Sustainable Development of Tsinghua University, Emission reduction path, technical and economic analysis and policy support for China to achieve carbon neutrality [M]. 2021.

Asian Institute of Technology

Final Report

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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 III

Project period: May 15, 2022-March 31, 2023

Report period: May 15, 2022-February 28, 2023

Asian Institute of Technology

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1. Participation in workshops/seminars/ conferences

1.1 Participation in IIASA's Quarterly workshops/working groups

a. IIASA Quarterly workshops (virtual): Actively participated and contributed in all the discussion sessions.

b. Annual EDITS Workshop 2022 at IIASA Austria: Joyashree Roy and her team (Joyee Chatterjee, Shreya Some, Md. Huzaifa Butt) participated in this workshop, held in August 2022 and actively contributed to the discussion sessions and social events.

c. COP27

- Joyashree Roy was a speaker at the EDITS organised side event at COP27 to discuss innovations for energy demand reduction, decarbonization of the urban environment and the construction sector, as well as pathways towards a net-zero society held on 10. 11. 2022. .https://iiasa.ac.at/events/nov-2022/edits-at-unfccc-cop27-high-services-with-low-energy-and-resource-demand-for-low**;** Title of presentation: Meeting multiple policy targets of development and mitigating global crises through demand solutions
- Joyashree Roy was the moderator at the RITE IIASA organised side event at COP27 side-event at COP27 "High wellbeing with low energy demand towards a modern net-zero society" held on 17. 11. 2022. https://iiasa.ac.at/events/nov-2022/rite-iiasa-side-event-on-edits-at-unfccc-cop27

d. AIT participants in IIASA-WG(s):

Industry (Joyashree and Shreya), Building (Joyashree and Huzaifa), Transport (Joyashree and Shreya), Data (Joyashree and Shreya), Protocol (Joyashree and Shreya), Narrative (Joyee), Synthesis (Joyashree)

e. Fast track paper activities: Participation from AIT

1.Energy Demand, Energy Efficiency and Lifestyle changes for South Asian Countries: A topic analysis (Lead: Shreya; Other team members: Huzaifa, Joyashree)

2.Communicating Demand Side Solutions (Lead: Joyee; Other team members: Joyashree, Shreya)

3.Demand Data (ASI) Mapping (Food sector- Lead: Shreya; Other team members from IIASA, BOKU)

4. Improved demand indicator (Indicator development- Lead with LBNL: Joyashree; Other team members: Shreya, Huzaifa)

5. Energy Debates_Young Scientist (Joyashree, Shreya)

1.2. Workshop/conference panel organised

a. Collaborative workshop on modelling demand side solutions through IDEEA Model (Indian Zero Carbon Energy Pathways): Workshop with policymakers and media, held on 7-8 September 2022 In Kolkata, India. (Annex I)

b. Panel discussion on "Open-Source Modelling of Energy System-Theory and Applications: IDEEA Model Application" held during ICUE, 2022 on 26 October 2022, organised jointly by South and Southeast Asia Multidisciplinary Research Network on Transforming Societies of Global South, SMARTS/SERD@AIT with other regional partners from India. https://youtu.be/hL18SnR6r4A. (Annex II)

1.3 Presentation in other relevant workshops/seminars/conferences

a. Joyashree Roy: Managing Agro-ecosystems under Climate Change @ International conference on Climate Change and Food security in South Asia, Dhaka, Bangladesh May 18-20, 2022. organized by Dhaka University in collaboration with WMO and FAO.

b. Joyashree Roy: Speech as Guest of Honour, "Demand, services and social aspects of mitigation: Implications for Bangladesh". Asian Network of Youth Volunteers Society, Organised by One Bangladesh, June 5. 2022

c. Shreya Some: Panelist at the Virtual Side Event of the Third Global Conference on Strengthening Synergies between the Paris Agreement and the 2030 Agenda for Sustainable Development (Tokyo, Japan, 20 - 21 July 2022)

d. Joyashree Roy: "Heat stress, Exacerbating Health Risks in India: Rethinking Approach to Health Service Provision", Organised by National Institute of Disaster Management, Ministry of Home Affairs, Govt. of India, CECCSD, IMPRI, India. July 26-28, 2022.

e. Joyashree Roy: New Era of Leadership: Economics of Sustainable Energy, Indian Oil Lead Talks 16th Edition, July 12, 2022, Corporate Office, New Delhi, India

f. Joyashree Roy: "Demand side solutions and links to SDGs". Event organized by UNESCAP, ADB, UNDP on Asia Pacific SDG partnership, July 12, 2022

g. Joyashree Roy: Climate Conversation and secrets of Prosperity in 21st Century: Subir Raha Memorial Lecture, Organised by Oil and Natural Gas Company Ltd., India , July 7, 2022

h. Joyashree Roy: Climate change and LDC graduation: A combination of demand side and supply side low-carbon energy transition diversifies and shifts investment patterns and

creates new economic opportunities. Organised by UN Committee for Development Policy 23-25 August, 2022.

i. Joyashree Roy: Addressed the Youths from various countries at YEA of AIT, Organised by RRCP, 2022 Youth Energy Academy on 11 Oct 2022

j. Joyashree Roy: Keynote address on Demand side climate solutions: shifting responsibilities to the public or empowering public?, 9th ICEF Annual Meeting, Tokyo, Japan on 5 Oct 2022

k. COP27
   - Joyashree Roy and Shreya Some spoke on demand side climate mitigation solutions at the IPCC Pavilion (Science for Climate Action) on 8. 11. 2022. https://www.youtube.com/watch?v=Vz8jrjkRcsk
   - Joyashree Roy talked in the "Meeting multiple policy targets of development and mitigating global crises through demand solutions" session, discussing climate strategies and the importance of including women in climate policy planning and implementation.
   - Joyashree Roy at the "10 New Insights in Climate Science 2022 and the COP27 Agenda" event at the Pathways to 1.5 pavilion.
   - Joyashree Roy, a panelist at The Singapore Pavilion on the Asian cities event, presented the principles of climate resilient development, explaining why they are important in Asian cities and discussing how they can be achieved through policies and the involvement of multiple municipal agencies and stakeholders.
   - Joyashree Roy spoke at a side event at German pavilion which was organised by Youths to understand how the future transformation can be managed without harming the future generation.
   - Joyashree Roy also moderated a session on Climate Justice and Gender at the IPCC Pavilion

l. Joyashree Roy: Delivered the "Veera Anstey Memorial Lecture" Indian Economic Association (IEA) " in the 105th Annual Conference (theme: "India at 75: Reviewing Indian Economy for Sustainable Development") of the IEA, at Dr. Shyama Prasad Mukherjee University, Ranchi, Jharkhand, India, 28th December 2022

m. Joyashree Roy: Chaired a session on "Decarbonization in Industries" at LCS-RNet 13th Annual Meeting, 16th December 2022

n. Joyashree Roy: Delivered webinar on the IPCC Working Group III Report on "How the Creation of a Low Carbon Lifestyle at the individual level is the key to fighting Climate Change", 8th December 2022

o. Shreya Some: Presented " Modelling energy demand, energy efficiency improvements and lifestyle change for South Asian countries: A topic analysis" in the IAMC Annual meeting, Maryland, USA, November 29- December 1, 2022. (Acknowledgement to EDITS)

p. Joyashree Roy and Shreya Some are invited to attend and speak on demand side climate mitigation solutions at the IPCC WGIII outreach event held on 23. 01. 2023 at Ahmedabad University, India.

2. Publication (with acknowledgement to EDIT)

a. Some, S., Roy, J., Chatterjee, J. S., & Butt, M. H. (2022). Low demand mitigation options for achieving Sustainable Development Goals: role of reduced food waste and sustainable dietary choice. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2022.133432 | IF: 11.072 | (Annex III)
Abstract: Food waste reduction at consumer end and balanced, sustainable healthy dietary choices featuring less meat and less processed food have clear climate change mitigation benefits. This paper synthesises the existing body of literature (2015 to 2022) following systematic evidence search and screening using Scopus database and Google Scholar to explore the link of these two demand side mitigation options with the Sustainable Development Goals (SDGs). Assessment shows that these mitigation options not only have synergies with energy saving (SDG 7) goal but are intricately linked with awareness and educational programmes (SDG 4 and SDG 12) along with technological solutions/innovation (SDG 9), much broader innovative policy designs (SDG 16) going beyond market incentives, and involvement of multiple social actors (SDG 17). In aggregate, synergies with the SDGs outweigh trade-offs. Trade-offs can be addressed through policy measures, strategic information sharing, creating partnerships among social actors. Specific interventions related to these two demand-side mitigation options are categorised using 'Avoid', 'Shift' and 'Improve' framework. This framework helps in categorising interventions/policy measures leading to various levels of emission reduction: incremental reduction through 'Shift' and 'Improve' interventions and absolute reduction through 'Avoid' interventions. A total of 92 interventions are identified. We summarised the social actors involved in implementing these interventions for each of the 'Avoid', 'Shift' and 'Improve' categories and outlined the scope for future research.

b. Roy, J., Some, S. (2022). E-Mobility for a Sustainable World: Unavoidable Automobility and Global South-North Perspectives. In Bhowmick, S and Ghosh, N. (Eds.). *Sustainable Development in Action: Examining Global North-South Divergences.* New Delhi: Observer Research Foundation and Global Policy Journal. (pp 100-118) https://www.orfonline.org/wp-content/uploads/2022/04/GP-ORF_Sustainable-Development-in-Action.pdf | (Annex IV)
Abstract: People and freight movement accounts for 15 percent of global greenhouse gas emissions (1). Not all mobility or even automobility demand can be fully avoided as it is

the mobility service that connects the point of demand and point of supply in an interdependent modern human society (see Figure 1 and Table 1). It is important then to consider how unavoidable automobility (mobility necessary to access services essential for human living) can be promoted bearing in mind the Sustainable Development Goals (SDGs), particularly SDG 7 (ensure access to affordable, reliable, sustainable and modern energy for all) and SDG 13 (take urgent action to combat climate change and its impacts) (2). Policymakers, spatial planners and service-delivery providers are the key actors to introduce any change related to mobility services, supplemented by information sharing to enhance user awareness and shape user behaviour (3). While digitalisation, information and communication, and interactive technologies may help in reimagining mobility services (4) their influence on the impact of mobility and energy demand on the environment is yet to be assessed (5). Mobility is not just for the physical transportation of passengers but for goods as well. Societies with a high interdependence through import-export of goods lead to an increased demand for automobility. Importantly, 90 percent of all global freight movement is by ships that run on fossil fuels (6).

North-South Binary: Existing literature on collective sustainable living (7) and eco-modern justice (8) highlights the need for mainstream research to go beyond traditional binary representations to show equity, such as North-South, rich-poor, developed developing, or Annex I- Non-Annex I countries. The north-south binary, which emerged amid globalisation from traditional political economy literature (9), trade literature (10), and geography (11), needs to be reframed in the wake of the global sustainability discourse and different economic levels across social groups. This paper views the Global South and North not as geographic regions but as 'social designations' for vulnerable communities due to political-social-economic factors in rich and poor countries (12). Social inequity in mobility is connected to levels of wealth, poverty and capabilities. People with a lower level of travel demand may satisfy one or a combination of the following factors: unemployment, low income, have a low ownership of vehicles, live in settlements that are less served by modern travel modes and services, have a lower capability to join the skilled labour market (13), and lack decent living standards (14). This group with a mobility deficit or deprivation will vary depending on the level of equity and inequity within a country. Unlike cooking fuel use, which leads to biomass burning and has environmental impacts, the mobility of a poor social group can typically be categorised under active mobility service and hence has a minimal contribution to the environment (Global South perspective). This paper focuses on unavoidable automobility, or the Global North perspective that cuts across all countries.

3. Work in Progress

3.1 Bottom-up country specific study

Two articles submitted to peer reviewed journal

3.2 Systematic review of literature

④ Asian Institute of Technology (AIT)

Energy Demand, Energy Efficiency and Lifestyle changes for South Asian Countries: A topic analysis- in progress. Preliminary results presented in IAMC 2022 (also mentioned under 1.3p)

3.3 Preliminary insights on infrastructure-disaster resilience-adaptation and energy demand implication

Literature review and write up are in progress

3.4 Micro grid, EV, policy and innovation including increasing digitalization and energy demand assessment (country case study)

a. Micro grid-India case study progressing through review of current status
b. EV and low carbon mobility transition in Pakistan: progressing for a publishable paper

3.5 Popular media Communication and energy demand

Progressing: targeting publishable paper, project proposal writing for small fund for social experiment

3.6 Special issue Journal with perspectives/research from the region

Proposal/concept note under preparation and search for possible host Journal

Annex I

1st IDEEA Offsite and Workshop
7th and 8th September 2022 | Peerless Inn, Kolkata

DAY 0	Tuesday, September 6
	Arrival of guests
7:30 PM onwards	*Dinner Buffet @ Oceanic, 1st floor*

DAY 1	Wednesday, September 7 Venue: Ego, Ground Floor		
7:30 - 8:30 AM	*Breakfast Buffet @ Oceanic*		
8:30 - 9:00 AM	**Introductions**		
9:00 - 9:15 AM	**Opening remarks** *Parthaa Bosu, Lead Advisor – Air Quality, Environmental Defense Fund*		
9:15 - 9:30 AM	**Setting the context** *Overview of how IDEEA model will be helpful to institutions and researchers.* *Dr Joyashree Roy, Professor of Economics, Founder of Global Change Program, Jadavpur University, Kolkata* *Dr Balachandra Patil, Chief Research Scientist, Department of Management Studies and Associate Faculty at Centre for Sustainable Technologies and Divecha Centre for Climate Change, Indian Institute of Science, Bengaluru*		
9:30 -9:45 AM	**State model - West Bengal** *Sourish Chatterjee and Arijit Mukherjee*		
9:45 - 10:00 AM	Discussions/ Q&A		
10:30 - 10:45 AM	**State model - Karnataka** *Abhishek Das, Samridh Sharma, and Varun Jyothiprakash*		
10:45 – 11:00 AM	Discussion/ Q & A		
11:00 – 11:30 AM	BREAK		
11:30 – 11:45 AM	**Group Activity – 1 - What should IDEEA do in the next five years?** *Dr Tarun Sharma, Assistant Professor, Indian Institute of Technology, Roorkee* *Brief overview of the session, group lead and note taker selected nominated for each group*		
11:45 - 12:15 PM	**Discussion in breakout groups in 3 teams**		
	Communication ***GROUP A***	***Research*** ***GROUP B***	***Partnership*** ***GROUP C***
	Nandini Das	*Sreelakshmi Ramesh*	*Sabuj Mandal*
	Dipayan De	*Agnirup Sarkar*	*Arijit Mukherjee*
	Shreya Some	*Sourish Chatterjee*	*Bishwanath Roy*
	Anupam Debsarkar	*Varun Jyothiprakash*	*Lavanya Padhi*
	Biswajit Thakur	*Balachandra Patil*	*Samridh Sharma*
	Abhishek Das	*Suchandra Bardhan*	*Joyashree Roy*
	Parthaa Bosu	*Piku Sen*	*Duke Ghosh*
	Aryama Sarkar		*Sudipta De*
12:15 - 12:45 AM	**Reporting back** *Lead member of the group reports back the ideas discussion followed by comments. Each team will get ten minutes to speak. Notes to be shared with Lavanya afterwards*		

12:45 – 1:45 PM	LUNCH
1:45 - 2:00 PM	**Modelling software and IDEEA** *By Dr Oleg Lugovoy, Lead Senior Economist* *IDEEA model, open model software landscape, positioning in the global scenario.*
2:00 - 2:45 PM	**Model Demonstration** *Abhishek Das, Samridh Sharma, and Varun Jyothiprakash*
2:45 – 3:00 PM	Discussions/ Q & A
3:00 - 3:30 PM	BREAK
3:30 – 3:45 PM	**IDEEA Research Overview** *Dr Oleg Lugovoy* *Brief overview of how the teams research topics is planned*
3:45 – 4:30 PM	**Research Topic Presentations - 1** *Abhishek Das, Varun Jyothiprakash, and Samridh Sharma* *Each presenter will get 10 minutes for presentation followed by 5 minutes for Q& A*
4:30 - 5:00 PM	**Research Topic Presentations - 2** *Sourish Chatterjee and Arijit Mukherjee* *Each presenter will get 10 minutes for presentation followed by 5 minutes for Q& A*
5:00 - 5:15 PM	**Day Summary** *Dr Anupam Debsarkar, Professor, Dept of Civil Engineering and Coordinator GCP, JU*
7:00 – 11:00 PM	Dinner Buffet @ Oceanic

DAY 2	**Thursday, September 8** **Venue: Senate 1, First Floor**
7:30 - 9:30 AM	*Breakfast Buffet @ Oceanic*
10:15 AM	IDEEA team reporting *IDEEA team members to arrive to Senate 1*
10:30 - 11:00 AM	Registration / TEA & COFFEE
11:00 - 11:15 AM	**Welcome Note** *Hisham Mundol, Chief advisor, Environmental Defense Fund*
	About IDEEA *Parthaa Bosu, Lead Advisor – Air Quality, EDF*
11:15 - 11:30 AM	**Model Overview and its global applications** *Dr Oleg Lugovoy, Lead Senior Economist, EDF* *Explains briefly applications of the tool in RE transition.* *Uses in policy making through feasibility analysis.*
11:30 - 11:45 AM	**How West Bengal can move towards a net zero energy systems by 2030** *Dr. Joyashree Roy, Professor of Economics, Founder of Global Change Program, Jadavpur University, Kolkata*
11:45 - 12:00 AM	**Role of modelling for energy transition in India** *Dr Balachandra Patil, Chief Research Scientist, Indian Institute of Science, Bengaluru*
12:00 - 12:50 PM	**What IDEEA could offer to West Bengal?** *Discussion moderated by Hisham Mundol*
12:50 – 1:00 PM	**Vote of Thanks** *Parthaa Bosu*

1:00 - 2:00 PM	LUNCH	
2:00 - 2:10 PM	**Group Activity -2 - Revisiting IDEEA way forward – briefing** *Dr Tarun Sharma and Dr Nandini Das*	
2:10 - 3:00 PM	**Discussion in breakout groups in 2 teams**	
	Group A Moderator: Dr Nandini Das	**Group B** Moderator: Dr Tarun Sharma
	Dipayan De	Sreelakshmi Ramesh
	Shreya Some	Agnirup Sarkar
	Anupam Debsarkar	Sourish Chatterjee
	Biswajit Thakur	Varun Jyothiprakash
	Abhishek Das	Bishwanath Roy
	Lavanya Padhi	Sabuj Mandal
	Aryama Sarkar	Suchandra Bardhan
	Sudipta De	Piku Sen
	Samridh Sharma	Duke Ghosh
		Arijit Mukherjee
3:00 - 3:15 PM	BREAK	
3:15 - 3:45 PM	**Reporting from the group activity** *Dr Nandini Das and Dr Tarun Sharma will provide group activity debrief*	
3:45 - 4:00 PM	**Concluding Remarks** *Dr Nandini Das*	
4:00 PM	**Vote of Thanks** *Parthaa Bosu*	
6:45 – 7:30 PM	Travel to Oh! Calcutta (Team Dinner)	

DAY 3	**Thursday, September 9th**
7:00 AM onwards	*Breakfast Buffet @ Oceanic, 1st floor*
	Check out of guests

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THE TIMES OF INDIA

'Bengal can achieve 100% transition to renewables'

TNN | Sep 9, 2022, 11.28 AM IST

KOLKATA: Bengal can plan an achievable transition from nearly absolute dependence on coal-based power to 100% renewables ahead of India's zero carbon power target of 2070. This has been indicated by an open-source model developed jointly by Jadavpur University's Global Change Programme, Indian Institute of Science (IISc) Bangalore and Environmental Defence Fund (EDF) of the US that have been collaborating on India's Zero Carbon Energy Pathways (IDEEA) project since 2020.

At present, over 84% of Bengal's power production is based on coal with hydro and solar making up the rest. The model looks into the spatial distribution of land by splitting it into a matrix of 250 sq metre each to then identify where to locate the renewable plants — solar and wind — to get the maximum potential and long-term reliability.

"The model integrates the variability of past 40 years using NASA's Modern-Era Retrospective analysis for Research Applications (MERRA) data to map and establish renewable power infrastructure in places that offer long-term reliability in producing power," said Joyashree Roy, professor of economics at JU and Global Change Programme founder advisor.

In a land-stressed state like Bengal, only 2% land would be required to install renewable infrastructure that would provide 100% power. "If we can bring in demand side flexibility, then demand for power can be reduced from 27 gigawatts to about 8 gigawatts and land requirement to just 0.5%," said Roy.

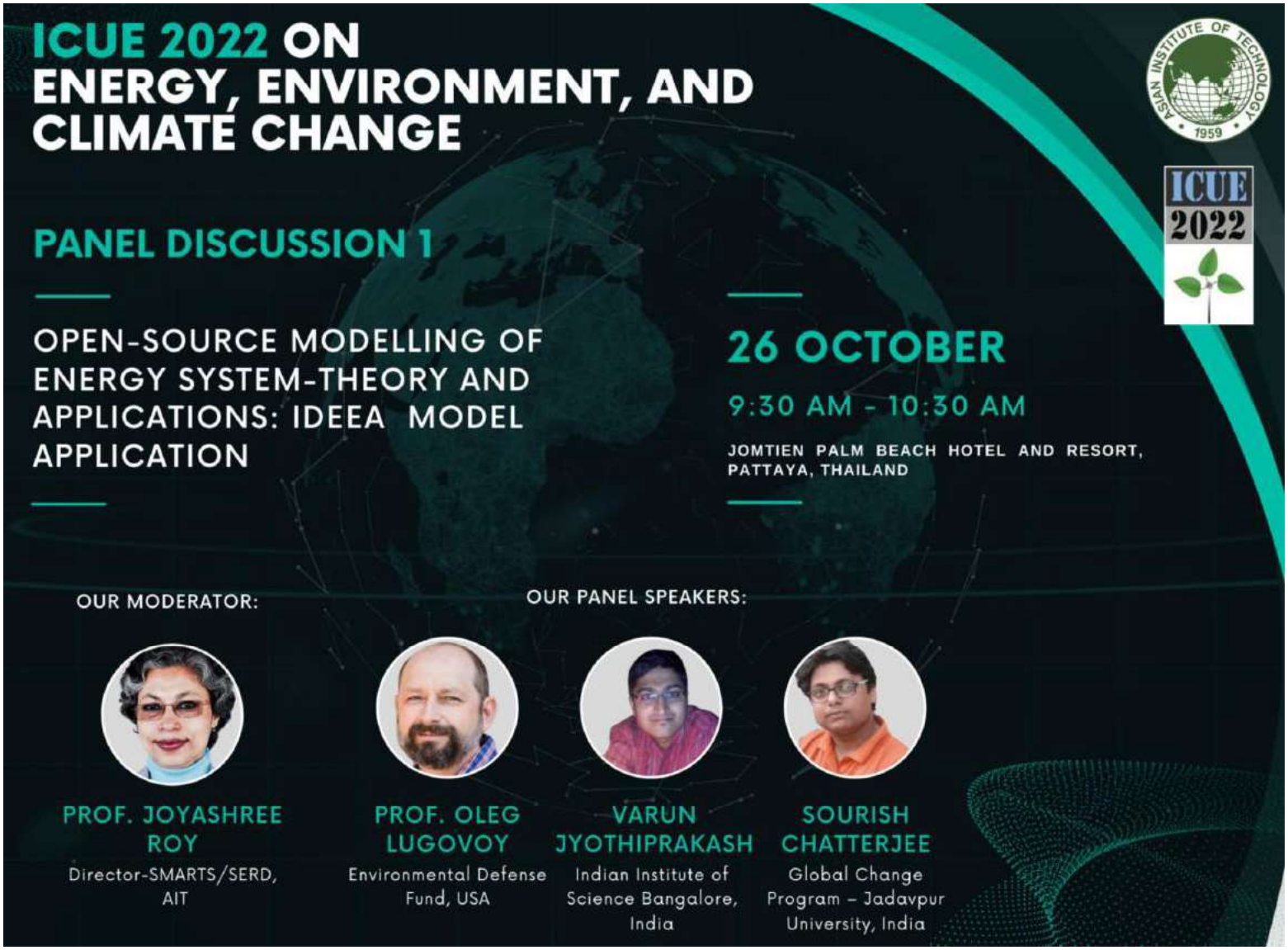
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IDEEA team and participants in the workshop





Annex II


ICUE 2022 ON ENERGY, ENVIRONMENT, AND CLIMATE CHANGE
ASIAN INSTITUTE OF TECHNOLOGY 1959
ICUE 2022
PANEL DISCUSSION 1
OPEN-SOURCE MODELLING OF ENERGY SYSTEM-THEORY AND APPLICATIONS: IDEEA MODEL APPLICATION
26 OCTOBER
9:30 AM - 10:30 AM
JOMTIEN PALM BEACH HOTEL AND RESORT, PATTAYA, THAILAND
OUR MODERATOR:
OUR PANEL SPEAKERS:
PROF. JOYASHREE ROY
Director-SMARTS/SERD, AIT
PROF. OLEG LUGOVOY
Environmental Defense Fund, USA
VARUN JYOTHIPRAKASH
Indian Institute of Science Bangalore, India
SOURISH CHATTERJEE
Global Change Program – Jadavpur University, India

Panel discussion on "Open-Source Modelling of Energy System-Theory and Applications: IDEEA Model Application" held during ICUE, 2022







Annex III

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Low demand mitigation options for achieving Sustainable Development Goals: Role of reduced food waste and sustainable dietary choice

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Sustainable consumption
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ABSTRACT

Food waste reduction at consumer end and balanced, sustainable healthy dietary choices featuring less meat and less processed food have clear climate change mitigation benefits. This paper synthesises the existing body of literature (2015 to 2022) following systematic evidence search and screening using Scopus database and Google Scholar to explore the link of these two demand side mitigation options with the Sustainable Development Goals (SDGs). Assessment shows that these mitigation options not only have synergies with energy saving (SDG 7) goal but are intricately linked with awareness and educational programmes (SDG 4 and SDG 12) along with technological solutions/innovation (SDG 9), much broader innovative policy designs (SDG 16) going beyond market incentives, and involvement of multiple social actors (SDG 17). In aggregate, synergies with the SDGs outweigh trade-offs. Trade-offs can be addressed through policy measures, strategic information sharing, creating partnerships among social actors. Specific interventions related to these two demand-side mitigation options are categorised using *'Avoid', 'Shift'* and *'Improve'* framework. This framework helps in categorising interventions/policy measures leading to various levels of emission reduction: incremental reduction through *'Shift'* and *'Improve'* interventions and absolute reduction through *'Avoid'* interventions. A total of 92 interventions are identified. We summarised the social actors involved in implementing these interventions for each of the *'Avoid', 'Shift'* and *'Improve'* categories and outlined the scope for future research.

1. Introduction

Food waste reduction at consumer end and changing dietary choices towards balanced, sustainable healthy diets featuring less meat and less processed food even after acknowledging the malnutrition issues in different parts of the world have high potential to reduce greenhouse gas emissions (IPCC, 2022; Hallström et al., 2015; Bajželj et al., 2014). Researchers (Malek et al., 2019; Taufik, 2018; West et al., 2014; Roy and Pal, 2009) have for long time been drawing attention to these non-supply side options for broadening mitigation actions. IPCC (2022) has assessed quantitative potential of demand side interventions highlighting the role of socio-cultural factors, infrastructure access in shaping individual dietary choices and potential co-benefits.

Demand side mitigation options include interventions focusing on socio-cultural factors, behaviour, lifestyle choices, changes in consumption pattern and level through individual and managerial intervention, new service delivery modes (e.g., packaging reductions, new ways of marketing, presentation of choices), infrastructure access (IPCC, 2022) and associated socio-technical transitions (Roy et al., 2021; Creutzig et al., 2020, 2018; Rosenzweig et al., 2020; IPCC, 2019). It is important to understand what different actions can influence human behaviour, choices, decisions towards food waste reduction and dietary choices (Banerjee and John, 2021; Creutzig et al., 2018).

While aiming for higher and faster mitigation actions, an important issue to understand is how various mitigation actions interact with the near-term targets of the UN 2030 Agenda for Sustainable Development: The Sustainable Development Goals (SDGs), which also addresses context specific targets for human wellbeing (Creutzig et al., 2022).

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Co-benefits from low demand climate mitigation options are also in discussion for over a decade now in the scientific community (Roy et al., 2012, 2021; Ürge-Vorsatz et al., 2014). Global scale assessments based on large number of scientific peer reviewed publications (IPCC, 2022; Frank et al., 2021; Hoegh-Guldberg et al., 2019; Roy et al., 2018) and rapid literature review on various mitigation options and their SDG links show positive links (synergies) with SDGs clearly outweigh negative links (trade-offs). However, all these past studies have considered supply-side and demand-side options at higher levels of aggregation or for select groups of options and did not consider detailed granular options/interventions in the selected domain of food and diet comprehensively.

Identifying the universe of possible mitigation interventions is important for implementation of actions. The Avoid-Shift-Improve (A-S-I) framework classify these interventions and helps in structuring policy measures as it reflects various levels of emission reduction: incremental reduction for *'Shift'* and *'Improve'* interventions and absolute reduction for *'Avoid'* interventions (Creutzig et al., 2022). This framework, is therefore useful to understand investment priorities, institutional roles (market, non-market, regulatory) and role of managers, choice architectures (IPCC, 2022) which goes beyond individual consumers.

Identification of key social actors (*'change agents'* in the society) who can externally trigger the changes is crucial. Existing literature do not present this comprehensively and systematically for two demand side mitigation options: food waste reduction at consumer end (only edible part, see FAO, 2011) and changing dietary choices towards balanced sustainable healthy diets featuring less meat and less processed food. There is no literature that provides a three-dimensional view of these two mitigation options: how are these two broad categories of options linked with the SDGs? What are the possible actions/interventions under each option and in which A-S-I category they belong to? Who is/are the primary social actors/*'change agents'* to trigger the change? Contribution of this paper to the existing literature is in bridging this knowledge gap.

In this backdrop, the objectives of this paper are three-fold: (1) understanding the links with SDGs for the two mitigation options: food waste reduction at consumer level, and balanced, sustainable healthy dietary choices featuring less meat and less processed food (results are presented in section 3.2), (2) identifying the interventions and classifying them into A-S-I categories (results are in section 3.3) (3) identifying and summarising social actors to help in understanding the target group in policy framing, and types of interventions for scaling up (results are in section 3.4). Methods followed in deriving the results are described in section 2. Discussion and conclusions are in sections 4 and 5 respectively.

2. Methods

In the existing literature, food waste reduction is a prominent strategy for resource saving, conservation, efficiency, intra and intergenerational equity issues, indication of incompleteness of market incentives, and also fits into the overarching goal of sustainable development (Creutzig et al., 2022; Hanley et al., 1997; Ethridge, 1973; Georgescu-Roegen, 1971). Over the past many decades this body of literature, both from theoretical and empirical perspective, has proliferated to show how both in the case of relative and absolute scarcity reduction of waste is a precondition for sustainable development. They are featuring in large global assessments (Pathak et al., 2022) and in innovative policy framework through waste hierarchy definitions. Strategies of circularity have been most comprehensively suggested by NEEA (Netherlands Environmental Assessment Agency) which define ten strategies- Refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover (Creutzig et al., 2022). In case of relative scarcity, it reduces both private and social cost to the system. This fits into the *'Improve'* and *'Shift'* categories in this paper. In case of absolute scarcity not only waste reduction but reduction in overall resource use is a precondition for sustainability. This fits into the *'Avoid'* category of this paper. By overcoming linearity in production system through recycling, technology innovation and infrastructure innovation, waste stream can be minimised (Fischedick et al., 2014). There are various related approaches in the literature such a circular material flow approach, industrial ecology approach. Literature and actions in the field of energy efficiency has evolved around this principle over many years (Saunders et al., 2021). Literature on the benefits of sustainable dietary choices is also growing exponentially.

This motivated us to synthesise the emerging literature from independent researchers from various countries and contexts to bridge the existing knowledge gaps. For doing this, we undertook a systematic search and screening of the existing literature on food waste reduction at the consumer end and changes in dietary choice towards balanced sustainable diet featuring less meat and less processed food to synthesise evidences.

This synthesis follows a rapid review of the literature published between 2015 and March 7, 2022. Elsevier's Scopus database is used for systematic search and Google Scholar is used for a focused search. The review methodology is explained in section 2.1 and Supplementary Material (SM) 1 in details for transparency and objectivity (Roy et al., 2021; Haddaway et al., 2015). Next, we reviewed the literature and mapped the synergies and trade-offs with the SDGs excluding SDG 13 which is on climate action. Here, we are mapping climate actions (i.e., the two demand side mitigation options) with the other sixteen SDGs. The methodology used to link these options with the SDGs largely builds on Roy et al. (2018), which was also applied in Hoegh-Guldberg et al. (2019), Some (2020) and similar approach was also followed in Honegger et al. (2021) and Creutzig et al. (2022). We explain it in sub-section 2.2. Lastly, we identify various interventions identified from the articles, classify them into A-S-I framework following Roy et al. (2021) and further into the social actors (*'change agents'*). The workflow chart is shown in Fig. 1.

2.1. Review methodology

Review methodology involves various steps starting from construction of search queries, article screening, data/information extraction to synthesis of findings. Based on our research objectives, first we construct search queries (see Table SM.1 in Supplementary Material (SM) 1 for details). We have two different sets of queries; one for food waste reduction and another for changes in dietary choices towards less meat and less processed food. Article screening is done following inclusion-exclusion criteria in a three-step hierarchical process: title, abstract and then full text (see Table SM.2 in SM1 for details). In the last step of article screening (Fig. 1), we recorded relevant information from each of the included study in a spreadsheet (see SM2) and a word document for cross checking (see SM3).

The information recorded include.

- Dimension 1: mapping food waste reduction at consumer end and changing dietary choices with the SDGs and its targets, quoting texts from the articles as synergies and trade-offs (for details see subsection 2.2 and SM4). We use the same spreadsheet format as used in the chapter 5 of IPCC SR1.5 (Roy et al., 2018).
- Dimension 2: identifying interventions and classifying them into A-S-I framework (see SM5)
- Dimension 3: identifying the social actors (see SM5) who can implement these interventions

2.2. Links with SDGs and assessment methodology

We follow three steps for assessing the link between the two demand-side mitigation options with the SDGs. First, the direction (positive or negative) of the (direct) link is recorded; positive links i.e., synergies are assigned a green upward arrow and negative links i.e., trade-offs are assigned a red downward arrow (see the 'Interaction' cell in SM4) For

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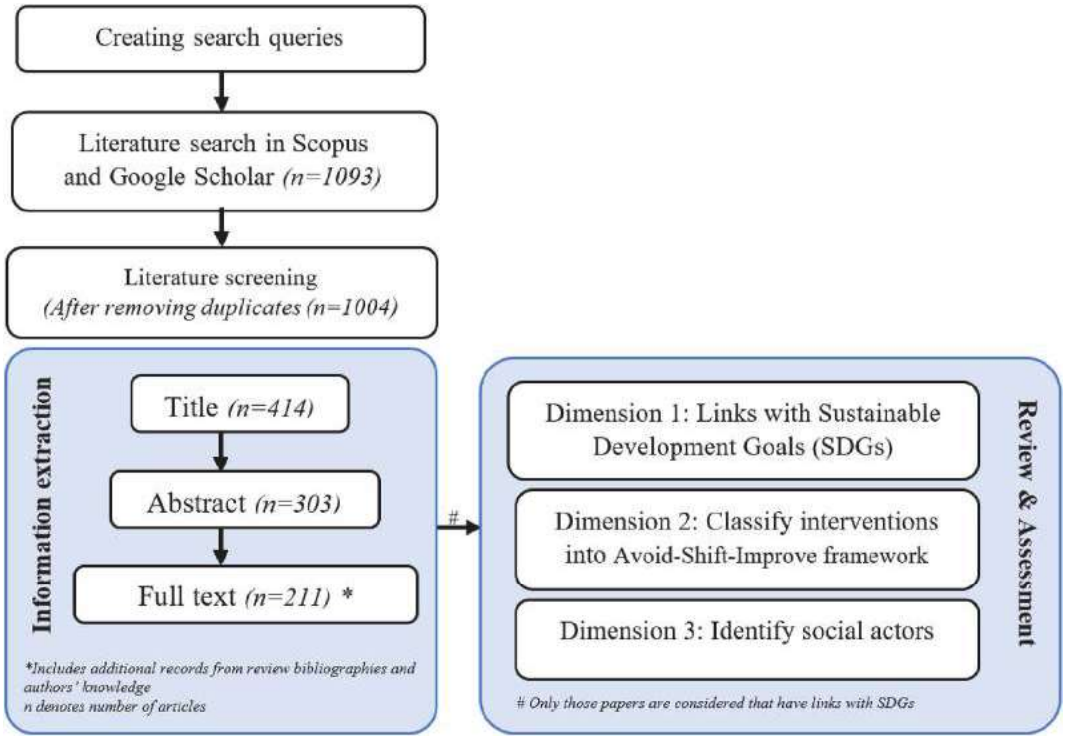


Fig. 1. Review methodology and Workflow chart.

any specific SDG, if we find that the literature indicates both synergies and trade-offs then we assign two arrows: green upward arrow and red downward arrow, separated by '/'. Associated targets of SDGs are reported as 'Targets' in SM4. Second, an impact score is assigned depending on the strength of the impacts (see the 'Nilsson Score' cell in SM4).

The score (Nilsson et al., 2016) is based on a **7-**point rating-scale (see Table 1). Synergies are assigned a score of +1 (enabling), +2 (reinforcing), or +3 (indivisible), while trade-offs are assigned a score of −1 (constraining), −2 (counteracting), or −3 (cancelling). Thus, the magnitude of the score, irrespective of the sign, provides an indication of strength of the link between the two demand-side option and the SDGs (Hoegh-Guldberg et al., 2019; Some, 2020; Roy et al., 2018). The reviewed literature do not specifically use the scores and links mentioned above, assignment of impact score in this review is based on the judgement of the claims of links mentioned in the reviewed literature by all the authors two of whom had been associated with the earlier review processes of the past studies mentioned above. Therefore, it may appear as subjective allocation of scores, however, the adopted methodology is stated in details with full transparency and the definitions provide scope of objectivity in choice of scores. So, four persons checking and coming in consensus makes the assessment stronger. To maintain consistency in this paper we laid down some rules following Nilsson et al. (2016): the highest positive score (+3) is assigned if the literature indicates that an intervention is intricately related with achievement of any specific SDG. If an intervention help/aid in achieving an SDG then (+2) is assigned. (+1) is assigned when evidences show that an intervention has potential/actually advances a specific SDG. The lowest negative link score (−3) is assigned if evidences point out that an intervention makes it impossible to achieve a particular SDG. (−2) is assigned if evidences show that an intervention act against the achievement of an SDG while (−1) is assigned if an intervention may limit the achievement of an SDG. (0) is assigned if the literature base suggests that intervention has no impact on a particular SDG. If literature indicates both synergies and trade-offs then we assigned positive and negative scores together.

In the last step, the level of confidence is assessed depending on the number of evidence extracted (i.e., articles) and literature agreement (see the 'evidence', 'agreement' and 'confidence' cells in SM4 and Table 2). Very high confidence (5-stars) implies robust evidence and high agreement. Similarly, very low confidence (1-star) depicts both low literature agreement and evidence (Mastrandrea et al., 2010). Based on the scores and the level of confidence we create the SDG chart (see Fig. 2 in subsection 3.2) to visually represent the synergies and trade-offs for the two demand-side mitigation options with the SDGs.

Table 1
7-point rating-scale.

Scale (Impact score)	Name	Explanation
+3	Indivisible	Inextricably linked to the achievement of another goal
+2	Reinforcing	Aids the achievement of another goal
+1	Enabling	Creates condition that further another goal
0	Consistent	No significant positive or negative interaction
−1	Constraining	Limits options on another goal
−2	Counteracting	Clashes with another goal
−3	Cancelling	Makes it impossible to reach another goal

Adapted from Nilsson et al. (2016).

3. Results

3.1. Review descriptive statistics

The search queries fetched a total of 1093 articles (for details see Table SM.1 in SM1). After three steps of screening, a total of 211 (2.1% of total) articles are found relevant for in-dept assessment (Table SM.3 in SM1). These 211 articles are from 31 different countries, 2, 5, and 24 articles are from multiple countries in Africa, Europe, and around the world, respectively. 9 are Global studies while 45 articles not specifying any geographic location. Most studied countries are the USA (n = 16), followed by UK (each with n = 15) (see figure SM.1 in SM1). 66 articles include interview/survey/focused group discussion-based studies, 56

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Table 2
Assessment of level of confidence.

Evidence

Degree of evidence	*No. of literature*	*Symbol*
Low	1-2	🕮
	3- 5	🕮🕮
Medium	6 - 10	🕮🕮🕮
High (Robust)	11 and above	🕮🕮🕮🕮

Agreement

Level of agreement	*% of evidences agreeing**	*Symbol*
Low	≤50% of the evidences agreeing	☺
Medium	51-75% of the evidences agreeing	☺☺
High	>75% of the evidences agreeing	☺☺☺

Note:* is not applicable if number of articles is only 1

Level of confidence

		Evidence		
		Low	Medium	High
Agreement	High	★★★	★★★★	★★★★★
	Medium	★★	★★★	★★★★
	Low	★	★★	★★★

★★★★★- very high ★★★★-high ★★★- medium ★★- low ★- very low

We also colour coded the cells in SM4 for better visual clarity: only synergies (green); only trade-offs (red) and both synergies and trade-offs (striped).

are review-based articles, 49 articles include qualitative analysis, mixed methods and experiment-based analysis, 28 articles are based on quantitative analysis which include measurement of environmental footprint/other modelling analysis, and 12 articles are on scenario analysis.

3.2. Link with SDGs

This subsection explains the links between the two demand-side mitigation options with the sixteen Sustainable Development Goals (SDGs).

3.2.1. Food waste reduction at consumer end

Review results clearly show food waste reduction helps in reducing resource use (SDG 8) like irrigation water (SDG 6), energy (SDG 7) and cropland. Making incremental changes in food waste reduction through sharing of leftovers reduces poverty (SDG 1) and hunger, thereby increasing food security (SDG 2). These changes have been brought through awareness campaigns and education programs (SDG 4), consumers having access to relevant information and awareness regarding other alternatives to food waste like recycle and reuse (SDG 12) (for case studies, see subsection 3.4.1). Local level policies (SDG 16; SDG 17) are required to implement food waste recycling interventions like composting and proper food waste management (SDG 11). Furthermore, upgraded technological solutions/innovation (SDG 9) like smart fridge, fridge cameras (Schanes et al., 2018), innovative packaging (like downsized packages, multipacks) are also reported as effective (Zeng and Durif, 2020).

This mitigation option may lead to some trade-offs with resource use through rebound effect. Studies (Reynolds et al., 2019a; b) have pointed out that reusing leftovers as next day lunch have chances of rebound effect i.e. this will save money which can be used for other types of consumption having negative environmental impact (SDG 12). This is a well-documented observation in energy efficiency related rebound effect literature also (Chakravarty et al., 2013).Trying to nudge consumer's behaviour to avoid food wastage by displaying posters in public eating places like canteens or cafeterias may lead to increased calorie intake (Lorenz-Walther et al., 2019), if the food proportion on plate is more than the required amount thereby affecting health adversely (SDG 3) (Alsaffar, 2016) so some understanding of the health impacts of over consumption is also needed. No direct link has been found with SDGs 5, 10 and 14 (Fig. 2). Overall, most of the links are reinforcing in nature (Table 1) thereby aiding the achievement of these SDGs.

3.2.2. Changing dietary choices towards balanced sustainable healthy diet featuring less meat and less processed food

Consuming meat substitutes like plant-based alternatives (legumes), insects, sea-foods improves nourishment, health (SDG 3) and also enhances food security (SDG 2). Seasonal food lowers the risk of serious health problems, such as heart disease, stroke, and some types of cancer

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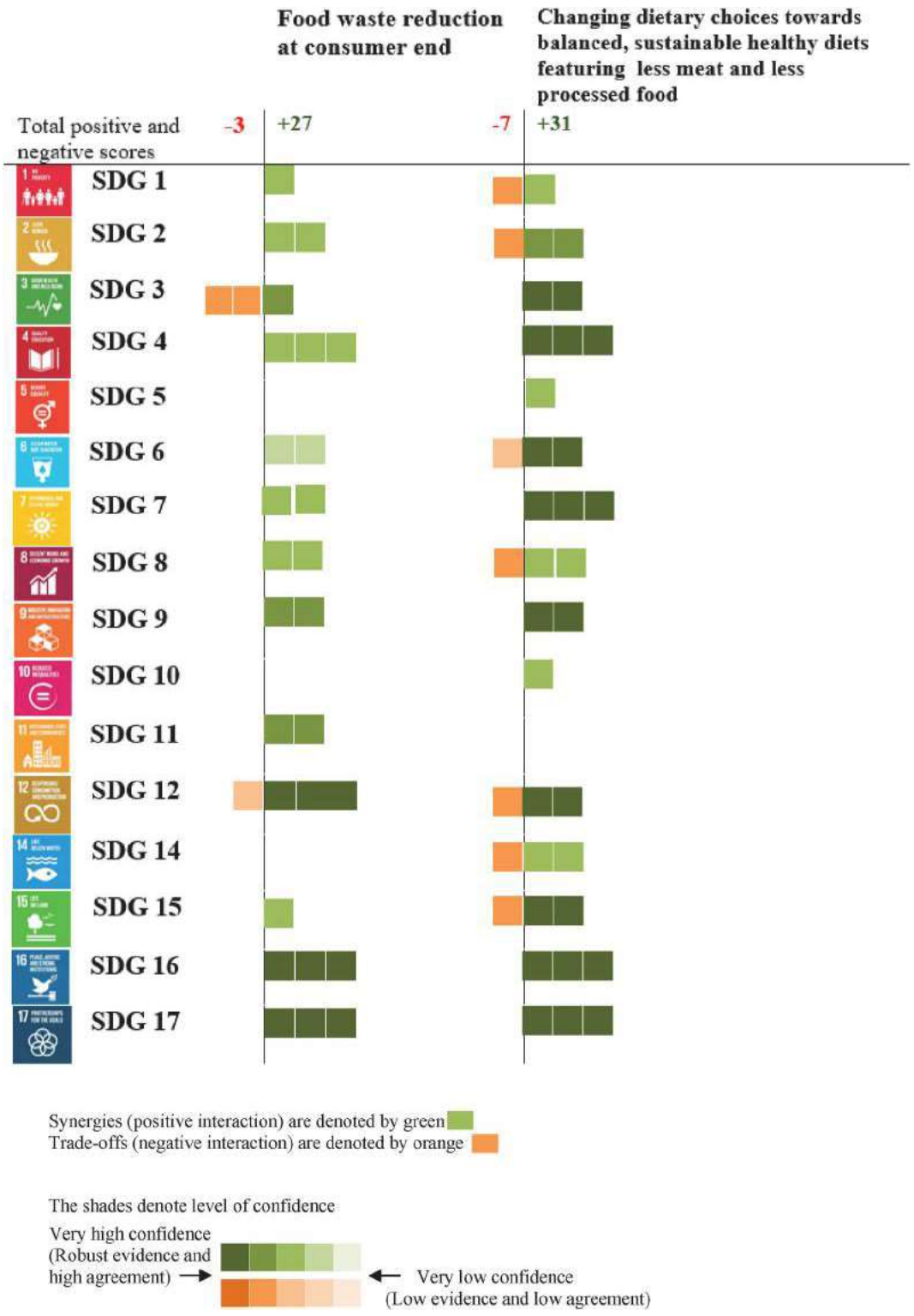


Fig. 2. SDG chart-showing SDG links (synergies and trade-offs) with individual demand-side mitigation options. This figure presents the information in SM4, length of the bars depicts interaction score (associated with 'Nilsson score' cell in SM4); green implies synergies while orange implies trade-offs (associated with 'Interaction' cell SM4), different shades are used to indicate different levels of confidence (associated with 'Confidence' cell in SM4). This figure clearly reveals that synergies exceed trade-offs for both the demand-side mitigation options.

(Żakowska-Biemans et al., 2019). Any reduction in meat consumption reduces the amount of energy required to produce animal feed and also in processing, transport, and distribution of meat and is therefore energy saving (SDG 7). Shifting towards plant and insect-based diets leads to water saving and reduce water pollution that occurs from slaughter houses (SDG 6) and less land use (SDGs 12, 15).

There are few trade-offs related to SDGs 1, 2, 8, 12, 14 and 15. Marques et al. (2018) pointed out that decrease in meat consumption may have negative impact on the economic growth of poorer countries who export meat products or those whose livelihood depend on

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livestock sector (SDGs 1, 2, 8). Therefore, providing social protection to pastoral communities and having nationally recommended diet plans for population suffering from malnutrition will help to minimise these trade-offs (Creutzig et al., 2022). Halldórsdóttir and Nicholas (2016) highlighted that locally produced cereals in Iceland may increase resource use like fertiliser (SDGs 8, 12, 15). Replacing meat completely with sea foods (ocean-based protein) may lead to overfishing, ocean acidification (SDG 14) and unplanned aquaculture which can cause invasion of alien species (Hoegh-Guldberg et al., 2019). These trade-offs can be minimised with expert consultation, inclusive management policies, monitoring and effective planning.

Educating people (SDG 4) via information campaigns, e-mails, posters etc. regarding the benefits of reducing meat and other processed food and having plant-based and less processed food are important. Partnership of policymakers and other stakeholders (consumers, producers, retailers and researchers) at national and international level (SDG 16 and 17) is required to achieve a mass shift towards diet featuring less meat and less processed food. Policies for promoting sustainable, balanced healthy consumption pattern (USDA, 2019) are already in place (SDG 16). More than 100 countries have developed their food and dietary guidelines based on their food availability, culinary culture and eating habits. (FAO, 2020). Revisiting them and promoting those in creating awareness from both health and environment benefit perspective will help in strengthening climate actions and social norms. The number of synergies exceed number of trade-offs. Most of the links are reinforcing in nature but SDG 4, 7, 16 and 17 are inextricably linked (see Table 1).

3.3. Interventions categorised into avoid-shift-improve categories

As discussed in Section 1, the A-S-I framework is generally used to structure policy measures that aim to reduce emission. It has been widely adopted to address rapidly transforming transport sector in developing countries since 2000. Recently, the A-S-I framework is proposed to apply beyond the transport sector (Creutzig et al., 2022; Roy et al., 2021; Creutzig et al., 2018).

In this paper, the interventions identified from each article (see SM2 and SM3) are classified into the three categories of the A-S-I framework (SM2). A total of 92 interventions have been identified: 34 for food waste reduction and 58 for sustainable dietary choices. 10 '*Avoid*', 10 '*Shift*' and 14 '*Improve*' interventions are identified for food waste reduction at consume end, and 15 '*Avoid*', 7 '*Shift*' and 36 '*Improve*' interventions are identified for sustainable dietary choice. Table 3 lists the interventions. For food waste reduction, *'Avoid'* interventions include those that help in reducing food waste or avoiding food waste completely, e.g. need based cooking which satisfies sufficiency criterion (IPCC, 2022); *'Shift'* interventions are those that aid in reusing (e.g. feeding to pets; using doggy bags; donating leftovers to food banks) or recycling food waste (composting) and *'Improve'* interventions help to build awareness in consumers which are supposed to alter their behaviour towards food waste (e.g. display of info-graphic posters in dining halls with messages on the benefits of reducing food waste, charging penalty on the amount of food wasted) and/or change lifestyle choices like carrying shopping list, buying fresh food. From the food hierarchy perspective (Papargyropoulou et al., 2014), our *'Avoid'* interventions are similar to the prevention of food waste while *'Shift'* interventions are similar to re-use and recycle of food waste.

Similarly, for sustainable dietary choices, *'Avoid'* interventions help in avoiding the demand for meat or highly processed food; *'Shift'* interventions help in shifting the demand for meat to other alternative less-GHG emitting food items (e.g., seafood, insect-based protein, organic food) or shifting the demand for highly processed food products towards less processed food products. On the other hand, *'Improve'* interventions help in awareness building that might lead to change in consumer behaviour towards less meat diet and less processed food consumption and/or consumers themselves taking incremental steps towards balanced, sustainable healthy diets choices.

3.4. Actors in A-S-I categories

Identifying wide diversity of social actors with different values, interests and concerns to tackle climate change are crucial to scaling up these interventions (Green et al., 2018). But how to do this is not always clear (Lorenz et al., 2019). Therefore, we tried to classify these interventions further by the social actors (*'change agents'*): institutions (e.g., educational-universities, governing-municipalities, media, and health-care), individuals (e.g., consumers, researchers, practitioners, activists) and supply chain partners (e.g., supermarkets, eateries, advertising agencies). Institutions help in creating awareness, advocating/promoting benefits of food waste reduction and sustainable dietary choices, and taking relevant policy measures. Individuals are groups of non-homogenous actors who can bring about the change by altering their own lifestyle, improving their own self-efficacy, setting examples for others and creating awareness in the society. Supply chain partners can bring in changes in their business processes to alter the behaviour of customers through choice architecture/menu engineering, nudging etc. (see SM5).

3.4.1. Social actors in A-S-I categories for food waste reduction at consumer end

'Avoid': Interventions from supply chain partners like providing access to mobile app-stock list with expiry tracker, smart fridge (Schanes et al., 2018) and sensors on food packages that detect spoilage (Conrad et al., 2018) help to change consumer behaviour towards avoiding food waste. Though these technological solutions are reported as effective initiatives but have no robust evidence due to lack of quantified studies (Reynolds et al., 2019a). Also, supply chain partners can improve food packaging by providing all necessary information related to expiry dates, best-before dates (Boulding et al., 2019) etc., because lack of such information forces consumers to discard edible food (Benyam et al., 2018) leading to more wastage. Individuals' (e.g. the house-cook) initiatives like cooking the amount of food needed depending on the number of guests reduces food waste but this meal planning (von Kameke and Fischer, 2018) is very uncommon (Schanes et al., 2018). Vásquez et al. (2022) mention that women plan more than men and therefore produce fewer food waste. Studies report saving money, saving the planet, saving hungry people and preventing guilt are the factors that motivates consumers to reduce food waste (Goodman-Smith et al., 2020).

'Shift': Shifting leftovers towards reusing, or recycling leftovers by putting in mixed/garbage bins instead of wasting involves additional actors like institutions (municipalities or local bodies). Also, ensuring environment-friendly treatment of the collected waste, e.g., composting is an important role on the part of these local institutions. Individual practices that helps in reusing leftovers include sharing them with relatives and friends, feeding to pets (Benyam et al., 2018) or using donation platforms. Restaurants can play their part by promoting doggy bags and redistributing leftovers at discounted prices (Boulding et al., 2019; Filimonau et al., 2019).

'Improve': Building awareness in consumers for changing their behaviour towards food waste requires involvement from researchers, practitioners including communication and marketing professionals, activists, policymakers. They can provide various information-based interventions using a range of 'delivery' techniques (Reynolds et al., 2019a) to improve food waste reduction behaviour (for details see SM5). Furthermore, consumers' initiatives like preserving and transforming leftover food by storing in fridge or using microwave (Hoek et al., 2017), buying less of perishable foods (Conrad et al., 2018) and preparing a shopping list to avoid excess food purchase (Zhang et al., 2018) reduces food waste.

Overall, based on the literature, for '*Improve*' interventions policymakers/governing bodies as a social actor have a larger role to play, for

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Table 3
The 92 Interventions classified into the *Avoid*, *Shift* and *Improve* categories.

Mitigation options	Interventions arranged in A-S-I categories		
	Avoid	Shift	Improve
Food waste reduction at consumer end	• Need based cooking • Meal planning • Reduction of portion sizes • Lower price for a smaller portion • Plate size adjustment • Food packaging with all relevant information • Downsized packages and multipacks • Discounts on close-to-date products • Access to inventory planning type tools • Smart fridge and related technologies	• Re-distributing surplus restaurant food among staffs • Selling surplus restaurant food to customers at discounted prices • Promoting the use of doggy bags • Changing waste collection system design • Changing treatment of collected wastes • Sharing leftovers • Feeding to pets • Usage of doggy bags • Participating in community food gardens • Preserving and transforming leftover food	• Display of information posters near eating halls • Smart technology-informative 'apps' • Changing school dietary guidelines • Redesign of class room syllabus regarding food waste • Offering flexible school lunch portion sizes • Information about food donation and freeganism • Consumer consciousness and attitude programs to avoid over purchasing and over consumption • Education to promote the importance of food waste prevention in terms of environmental, social, and economic impacts/face-to-face door-stepping campaigns • Public promotion of food waste reduction by a respected person • Food waste tax • Storing in fridge • Buying fresh food items • Purchasing less-perishable foods/using shelf-stable items • Using shopping list
Changing dietary choices towards balanced, sustainable healthy diets featuring less meat and less processed food	• Providing broader variety of vegetarian dishes in menu • Global movement: Meatless Mondays • Becoming a vegan • Becoming a vegetarian • Becoming a pescatarian • Increasing fruits consumption; Replacing snacks with fruit • Replacing cheese with vegetables • Replacing soft/hard drinks with tap water • Selection of local food/ Shopping in smaller shops, farmers markets • Selection of seasonal food • Have low fat and low sugar food products • Purchasing and consuming food products that respects animal welfare • Reducing overconsumption • Avoiding consumption of discretionary foods • Lowering total energy intake by avoiding beverages	Shift to balance, sustainable healthy diet options: • Vegan • Vegetarian • Organic food • Plant based diet • Ocean based protein diet • Others: Insects, Mycoproteins, algae • Teetotalism: Abstaining from alcoholic beverages	• Promotion of meat alternatives • Promotion of organic food • Making plant-based protein available in stores • Organising plant-based protein in stores such that is accessible and easily visible • Providing vegan cook books • Promoting vegan cooking shows • Free tasting stations/vegetarian food fairs in supermarkets for meat substitutes • Recommendation on daily consumptions per product group • Providing discounted healthy options • Providing text messages about health and/or environmental benefits • Providing Eco labels/carbon labels • Training chefs for preparing tasty dishes with meat substitutes • Nudging/menu engineering • Information campaigns to raise awareness regarding the environmental impacts of less meat and less processed food • Information campaigns in order to raise awareness of having sea-food • Imposing tax: meat and dairy tax; unhealthy food tax • Increasing price of meat • Advocating the health benefits of increasing diary consumption but reducing processed meat • Advocating the health benefits having cereals, pulses/starchy foods/legumes, plants • Advocating the health benefits of having ocean –based protein • Healthy eating counselling • Promoting healthy food choice: Reducing consumption of discretionary foods/convenience food • Promoting healthy food choice: reducing the consumption of alcoholic drinks • Promoting healthy food choice: Reducing non-alcoholic beverages • Promoting healthy food choice: Having low fat and low sugar food products • Promoting healthy and sustainable food consumption in schools, including a weekly 'meat-free' day • Halving meat consumption/Smaller portion of meat • Increasing diary but reducing meat • Beef reduction with chicken/pork/poultry • Supporting and promoting vegan diets through website and social media presence, events, workshops, etc. • Creating platforms that provide tailored information (e.g., recipes; cookalongs; environmental, health, and nutrient information); live expert and connecting them with other similar groups (online communities or local groups); Celebrity endorsement; social media influencers • Peer-to-peer marketing • Reducing processed meat/food • Buying locally grown produce • Becoming a Flexitarian • Observing Meatless days

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Note: Some interventions can be in more than one A-S-I category.

'*Shift*' interventions individual consumers have a greater role to play while for '*Avoid*' interventions supply chain partners have important roles to play (Fig. 3).

3.4.2. Social actors in A-S-I categories for changing dietary choices towards balanced sustainable healthy diet featuring less meat and less processed food

'Avoid': Consumers' own initiatives to avoid meat consumption completely include becoming a vegan, vegetarian or pescatarian (fish eaters). Consumers' cautiousness towards health is the main driver behind avoiding highly processed food (Alsaffar, 2016). Strategies of avoiding highly processed food as mentioned in the literature include avoiding snacks, cheese in between meals (van Dooren et al., 2018), replacing them with seasonal fruits and vegetables (Żakowska-Biemans et al., 2019), substituting soft drinks, non-alcoholic beverages with potable water (Reynolds et al., 2019a), reducing alcoholic drinks (Yu et al., 2018) and buying food from small farmers and local shops (Schanes et al., 2018). Initiatives from supply chain partners like canteens and restaurants include broadening the variety of plant-based, insect-based dishes they offer (Orkusz et al., 2020; Rust et al., 2020), can motivate customers to avoid meat.

'Shift': Shifting towards a less/low meat diet, plant based diet (Lynch et al., 2018), various other alternative protein diets like edible insects (Orkusz et al., 2020), and sea-based protein diets (Hallström et al., 2019) are being promoted globally by actors like policymakers and health practitioners due to their health and environmental benefits. However, the lack of skills on how to cook these meat alternatives is the main barrier in this shift (Kwasny et al., 2022; Varela et al., 2022).

'Improve': Consumers' behaviour to change to less processed diets is motivated by health consciousness so health practitioners have a great responsibility of advocating greater consumption of fruits and vegetables, avoidance of high energy intake, moderate consumption of beverages (Yu et al., 2018). Supply-side actors e.g. manufacturers through their public relations and marketing departments, supermarkets, advertising agencies have a role to play in changing consumer purchase behaviour (Hoek et al., 2017) by increasing the accessibility, visibility and availability of meat alternatives-in their shelves (Hoek et al., 2017), peer to peer marketing and creating platforms that provides tailored information; promoting discussion with live experts, and cookalongs (Trewern et al., 2022). Marshall et al. (2022) highlighted that describing vegetarian foods using meat related terminology increases consumers' willingness to consume such food. Specifically, food suppliers or retailers can have free tasting stations/vegetarian food fairs for meat substitutes (Ruzgys and Pickering, 2020) and can distribute vegan cook books and create mobile apps that provides easy-to-cook vegetarian dishes (Schenk et al., 2018). Consumers' own initiatives to reduce meat consumption include several lifestyle choices like becoming a flexitarian i.e. occasional inclusion of red-meat in diet (Armstrong Soule and Sekhon, 2019), substituting red-meat with chicken (González-García et al., 2018) and observing at-least one meatless day a week.

Overall, based on the literature, for *'shift'* interventions governing bodies and health care systems have a larger role to play as social actors by advocating complete shift towards meat alternatives through dietary guidelines. For *'improve'* interventions supply chain partners, individual consumers, and researchers, practitioners, activists have a major role to play through nudging, supporting and promoting less meat diets through social media. For '*Avoid*' interventions individual consumers have important role to play (Fig. 4) by changing their lifestyle choices.

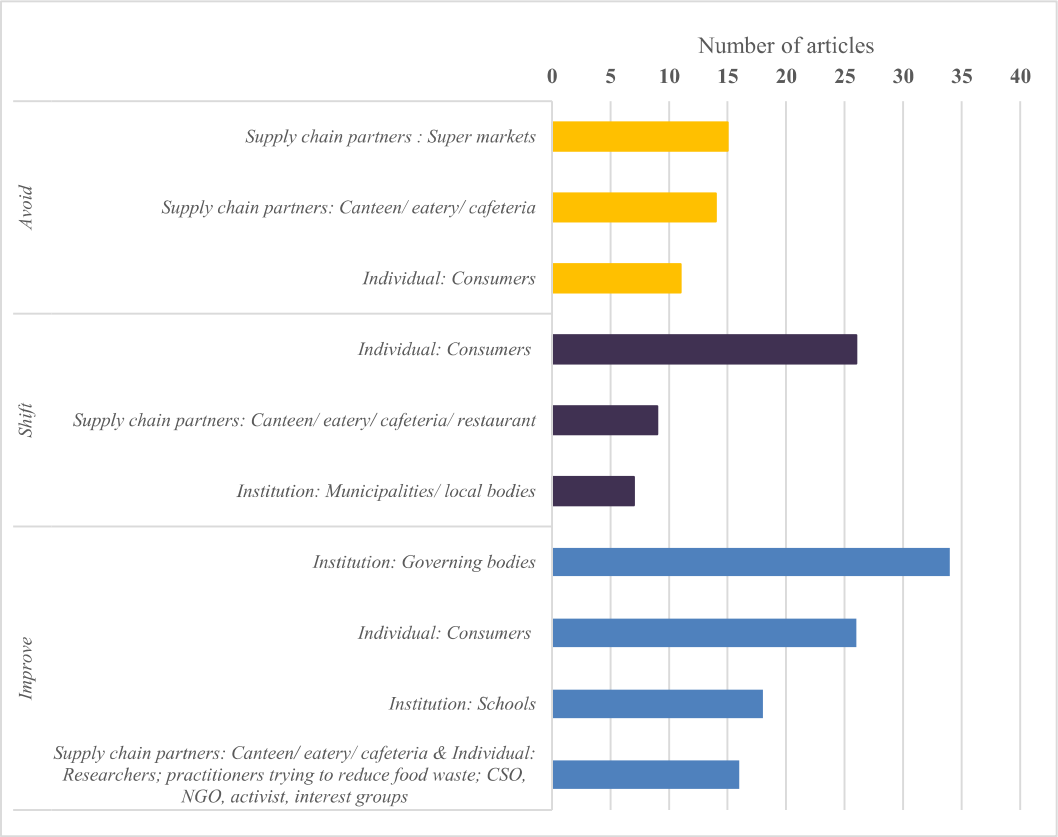


Fig. 3. Role of social actors in advancing *Avoid, Shift* and *Improve* interventions related to food waste reduction at consumer end. Length of bars represents number of articles/evidence.

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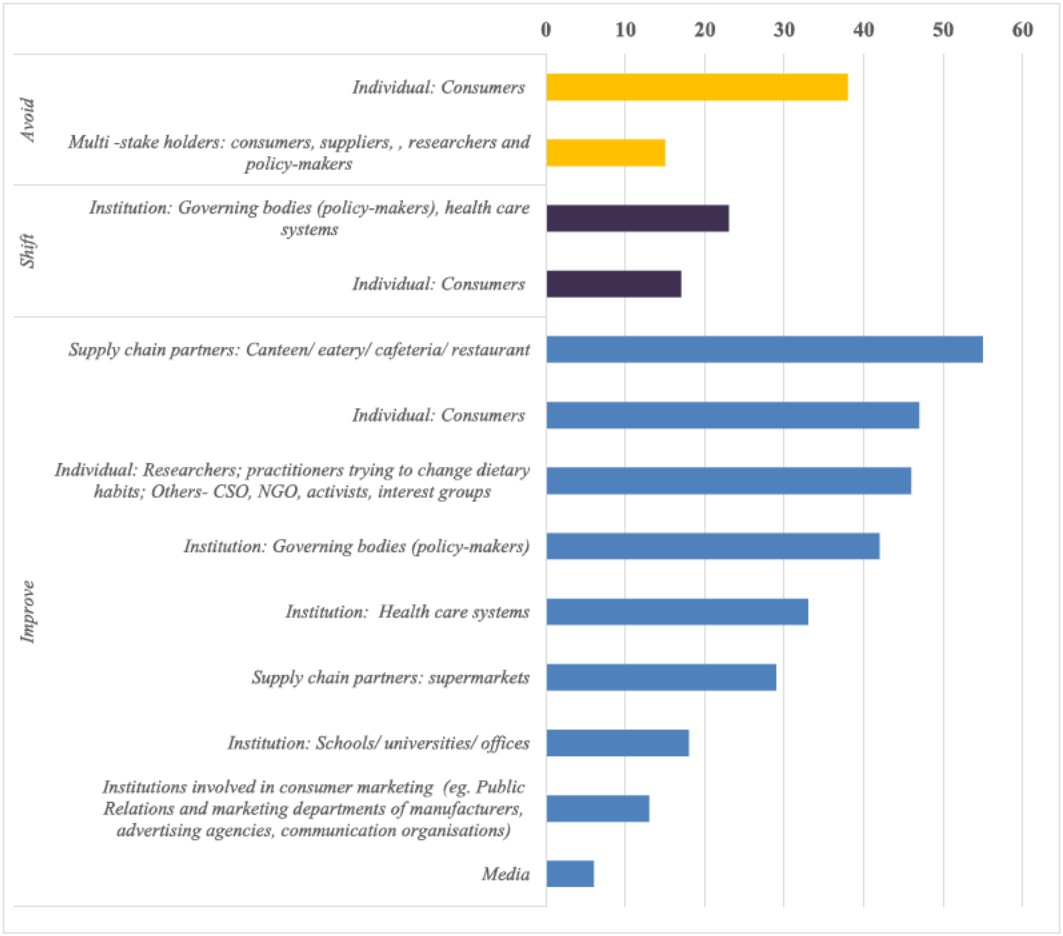


Fig. 4. Role of social actors in advancing *Avoid, Shift* and *Improve* interventions related to changing dietary choices balanced sustainable healthy diet featuring less meat and less processed food. Length of bars represents number of articles/evidence.

4. Discussions

4.1. Food waste reduction at consumer end

Food wasted is at least directly related to equivalent waste in energy resources used in its production and indirectly related to energy resources used for fertiliser production, other inputs and in distribution such as energy used in storing and transportation. Not only energy waste, food waste also relates to waste of water that has gone into the production of food. Our results show that reducing food waste reduces energy use/demand (SDG 7), water use/demand (SDG 6) and land use/demand (SDG 15) for food production. Conrad et al. (2018) reported that 1 pound of food was wasted by average Americans every day from 2007 to 2014 and 30 million acres of cropland were used to produce this food every year. Also, halving food loss and waste can achieve 12% reduction in water (Jalava et al., 2016). Figure SPM.6 in IPCC (2022) shows that the land spared through food demand reduction can be used for reforestation which provides large emission mitigation potential.

Awareness campaigns and education programs (SDG 4, 12) are pivotal to motivate consumers in reducing food waste. A study in Portugal found that 70% of the respondents recycle inorganic waste after participating in education campaigns (Pinto et al., 2018). However, this option does not reduce food demand/production *per se* as this is end-of-the-pipe option. Highest mitigation potential lies in reducing food waste that can eventually show up in reduced demand on land for food production (IPCC, 2022). Price instruments like fees, taxes have been found to be less effective in many countries/contexts than well-defined regulations (Schanes et al., 2018).

Various social actors have a role to play in avoiding food waste. For example, food service providers like canteens in various institutions like educational, office etc., restaurants and hotels can play their part by customising/reducing the portion size, using different sizes of utensils/plates (Lorenz-Walther et al., 2019) and charging lower price for smaller portions (Reynolds et al., 2019a). In scaling up such changes in service provision needs education/awareness programs targeted at canteen managers and staffs, training on choice architecture (Creutzig et al., 2022) which further allows customers to make better choices from menu charts. An experiment conducted in a Norwegian hotel reported 19% reduction in food waste due to reduction in plate size (Reynolds et al., 2019a).

Manzocco et al. (2016) found that 45% of the food wasted are discared as rubbish, 25% are fed to pets, around 25% are used for (home) composting and only 5% are used for donations. Shifting food waste for recycling needs to be supported by appropriate infrastructure for food waste collection (IPCC, 2022). For e.g., green bin residential food waste program in Australia (Benyam et al., 2018) has proved effective in changing household's food waste behaviour. Sharing or reusing leftovers are being promoted by several collective initiatives like organising food banks (Morone et al., 2019) e.g. Saudi Food Bank Initiative, Plan Zheros in England, Food Cloud in Ireland (Secondi et al., 2020; Mu'azu et al., 2019). Restaurants/eateries play a vital role in promoting the use of doggy bags by making doggy bags a common practice from food service provider side than to waiting for consumer to request for doggy bags because in some cultures asking for doggy bags leads to embarrassment (van Herpen et al., 2021). Restaurants can also re-distribute leftovers among staffs (Filimonau et al., 2019). The pan-European

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'Too Good To Go (TGTG)' smartphone app allows customers to purchase discounted restaurant meals at the end of a day thereby minimising the amount of food wasted (Filimonau & Delysia, 2019).

Interventions that are being tested and promoted to nudge (incrementally alter) consumer behaviour towards food waste are listed in Table 2 and SM5. One such intervention is displaying information posters near eating halls or sending information-e− mails on the benefits of reducing food waste (Young et al., 2017). A university canteen-based study in Germany reported that 86% of the respondents who could recall the poster displayed regarding food waste reduction in their canteen had no-leftovers in their plates (Lorenz-Walther et al., 2019).

Collaborative efforts among social actors are emerging. The Hungarian Food Bank Association in collaboration with TESCO -a retail supermarket-created a website to make consumers aware of food waste and provided tips on how to reduce food waste via e-mails. This had helped in improving food waste knowledge and skills in 265 households all over Hungary (Boulding et al., 2019). Charging a high disposal fee of wasted food from high-income households in China also helped reduce food waste (Zhang et al., 2018). In Japan, an education program 'Bento Day' is celebrated in elementary and junior high schools since 2001 where students need to cook and prepare food at home to bring to school for lunch. This helps in reducing food waste both at home and in school because students understand the hard-work needed to prepare food (Lindgren et al., 2018). In the USA, dietary reformulation in schools resulted in a 28% reduction of vegetable waste (Schwartz et al., 2015), while emphasizing on topics related to food waste reduction in school curriculum reduces 33% food waste from main dishes in Portugal (Martins et al., 2016).

In Fig. 5, we list 21 interventions encompassing 5 specific social actors (consumers, eatery, super markets, schools and governing bodies) who can reduce food waste inside home and outside home (details in SM5). Many interventions are to be managed externally to help reduce waste at consumer end.

4.2. Changing dietary choices towards less meat and less processed food

Shift towards plant-based diets which are in line with standard dietary guidelines can decrease global mortality by 6–10% in 2050 compared to a reference scenario (Dhiman, 2018). Shift to New Nordic Diet (i.e., increased consumption of fruits and vegetables, reduced consumption of meat and sugared drinks) could save about 6500 Disability Adjusted Life Year (DALY) per year from cardiovascular disease (Jensen et al., 2015). Resource saving (SDGs 6, 7, 8, 12, 15) potentials of the above mitigation option are highlighted in the literature. Goldstein et al. (2017) reported significant reductions in water consumption (1.30 ± 12.00 km^3) and land use (22300 ± 190100 km^2) due to substitution of 10%, 25% and 50% of ground beef with plant-based burger at the national scale in the USA.

Less meat and less processed food in diet have synergies with SDGs 2 and 3. Shepon et al. (2018) reported 2–20 times more nutritionally similar food production per unit of cropland in the USA if plant-based replacements are made for each of the major animal meats (beef, pork, dairy, poultry, and eggs). With current level of knowledge, complete replacement of meat and dairy products from diet for all may not be feasible given the animal based micronutrients (e.g., calcium and vitamin D) required by human body (González-García et al., 2018) but by optimising meat consumption following healthy dietary guidelines has positive impact on public health (SDG 3), reduced risk of obesity, cardiovascular diseases and cancer due to reduced intake of saturated fat (Jackson et al., 2022).

Consumers' willingness to avoid meat depends on health reasons, respecting animal welfare (Żakowska-Biemans et al., 2019), environmental concern and religion (Malek et al., 2019). The United States Department of Agriculture (USDA) in their official website 'ChooseMyPlate' has recommended seafood rich in omega-3 and fatty acids at least twice a week as the main protein food (USDA, 2019). Supartini et al. (2018) reported 5 times increase in the desire to buy fish compared to 10 years ago in UK and Singapore. The reasons given are change in dietary pattern of consumers with younger age, cheaper price and health benefits. Eker et al. (2019) explained that diet change behaviour is mostly influenced by social norms and self-efficacy. From a cross sectional survey across UK, Culliford and Bradbury (2020) reported four major factors behind sustainable diet choice motives: health, taste, cost, and environmental sustainability. Therefore, consumers' choice of lifestyle

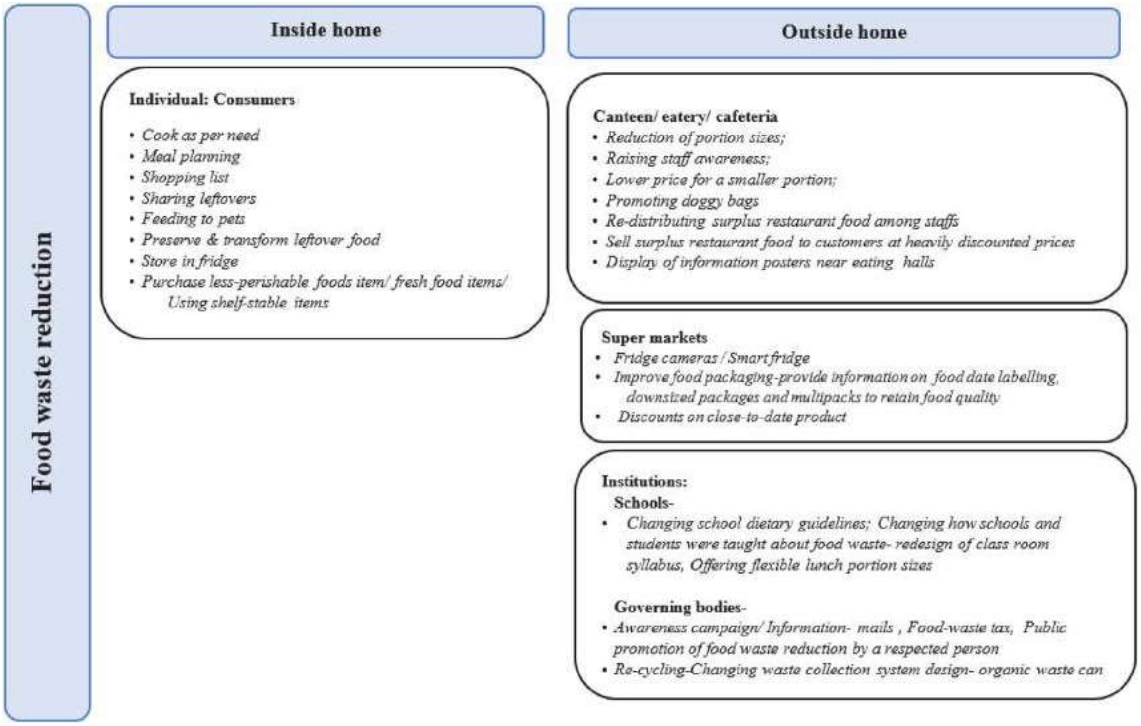


Fig. 5. Interventions (in italics) and social actors (in bold) who can help in reducing food waste at consumer end.

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(vegan, vegetarian, etc.) is very important. However, studies have also pointed out that if meat consumption is rooted in social and cultural factors then knowledge on adverse health impacts is insufficient to drive the change (Sahakian et al., 2020).

Recurring awareness and information campaigns regarding the environmental and health impacts of meat consumption involving policymakers and health practitioners can improve consumers' choice towards less meat diet (de Boer and Aiking, 2017). Kaljonen et al. (2020) found that nudging customers persistently has two effects: restaurants get more freedom to develop new tastier meat-free dishes and can get customers accustomed to those new dishes, while customers get more satiating meat-free options. Global movement like 'Meatless Mondays' started in 2003 for encouraging consumers to have meat-free meals once a week (Meatless Mondays, 2019) has now spread over 40 countries, and in 20 different languages. New studies are trying to see the effectiveness of online communities on changing consumers behaviour towards less meat diet. Trewern et al. (2022) found that 'ask the expert' videos are effective in UK. It is also suggested that market interventions like food greenhouse gas tax or meat and dairy tax (Röös et al., 2018) or increasing price of meat can help in reducing meat consumption. A study, Charlebois et al. (2016) designed to evaluate the response of consumers to increase in beef prices in Canada revealed that 37.9% reduced or stopped beef consumption altogether due to higher prices.

Studies in European countries have found that women are more interested in plant-based diets than men and that men associate meat consumption with masculinity (physical strength and power) (Duarte et al., 2020; Peltola et al., 2020). Also, women are primarily involved in cooking and shopping, so their roles are very significant (García--González et al., 2020). Therefore, it is a good opportunity to influence them to become '*change agents*' for promoting sustainable consumption in the society.

Several interventions that support consumer behaviour change can be effectively implemented by practical and managerial actions. In Fig. 6 we provide a list of 37 such interventions encompassing 9 specific social actors (consumers, eatery, supermarkets, schools, governing bodies, health-care systems, marketing agencies, practitioners, media) who can support in changing dietary choices towards low/less meat diet and less processed food (details in SM5) for a low carbon future.

5. Conclusions

Implementation of the two broad climate change mitigation options: food waste reduction at consumer end and enhancing choices in favour of balanced, sustainable healthy diet featuring less meat and less processed food needs understanding of interventions that can enable these changes. Systematic evidence search and literature screening using the Scopus database and focused search in Google Scholar helped in accessing a rich body of existing literature albeit the majority of the studies being from developed country contexts. Reviewing this rich body of literature (211 articles from 2015 to 2022), we identified 92 interventions (Table 2) that have demonstrated results in implementing these two broad options and also advancing multiple Sustainable Development Goals. Social actors who are instrumental in implementing these interventions are also identified for each of these 92 interventions

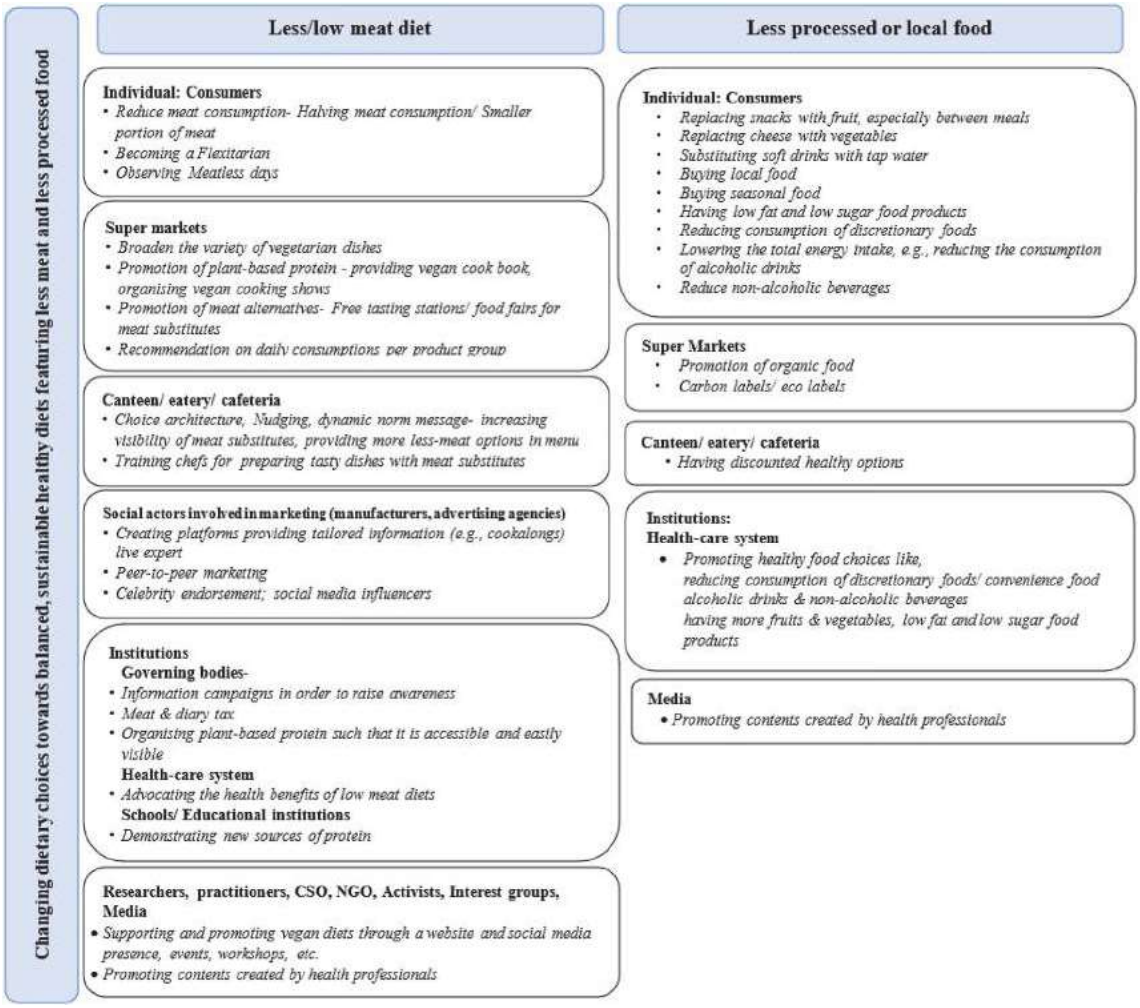


Fig. 6. Interventions (in italics) and social actors (in bold) who can help promoting dietary choices featuring low meat and low less processed food diets.

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(Figs. 5 and 6 and SM5). However, these 92 interventions should not be considered as an exhaustive list because there may be more innovative ways to implement them which new research can further explore. It is important to note that these interventions are context specific and their effectiveness will vary based on different milieu. This calls for multi-disciplinary research, multilevel interventions and cross sectoral collaboration among stakeholders, specifically practitioners and policymakers.

Assessment of SDGs links (Fig. 2) clearly show that it is not all win-win outcomes. Overall, synergies of these two broad mitigation options with SDGs outweigh trade-offs. Reducing food waste at consumer end has clear synergies with SDGs 1, 2, 4, 6, 7, 8, 9, 11, 15, 16 and 17. While for sustainable dietary choices, clear synergies exist with SDGs 3, 4, 5, 7, 9, 10, 16 and 17. Major trade-off in reducing food waste is with SDG 3 because avoiding food waste without changing food choices can lead to increased calorie intake. The literature also reports that such trade-off can be addressed by monitoring portion size, and being careful about nutritional need of the consumers groups i.e., through careful health expert consultation and consumer-group specific health developmental attainment. Waste reduction for improving resource-use efficiency is a win-win option if rebound effect in consumption can be avoided with market instruments and non-market strategic information dissemination programmes, infrastructure development for recycling, innovating and upgrading technologies like food sharing apps. Literature flag a major awareness gap. Majority of the eatery managers are not aware of reduced operating cost implications of food waste reduction and redistribution initiatives.

Major trade-offs for sustainable dietary choices exist with SDGs 1, 2, 8, 12, 14, 15 because decrease in meat consumption may have negative impact on the economic growth of poorer exporting countries and replacing meat with ocean-based protein may lead to overfishing and unplanned aquaculture. These can be addressed by providing social protection to pastoral communities to compensate for livelihood loss due to reduction in demand for meat. For people with malnutrition, nationally recommended diet plans can be strengthened through institutional mechanism, inclusive management policies, monitoring, and effective planning while producing alternative food (e.g., limiting overfishing). Promoting health benefits of balanced, sustainable healthy diet has extremely important role to play. Role of choice architects in presenting options linked to pricing incentives, nudge mechanisms can also reduce trade-offs.

Some structural and knowledge barriers prohibit consumers to take actions like lack of information/skills on how to cook meat alternatives, lack of knowledge on product expiry date labels, inability to buy local food due to distribution issues. These barriers can be reduced by actions from diverse social actors like supply chain partners (e.g., supermarkets, eateries, manufacturers, and agencies involved in marketing) by creating/promoting/organising platforms to provide tailored information on various meat alternatives/recipes, improving food packaging, and by institutions (e.g., governing bodies—municipalities and healthcare) who can look into and resolve local food distribution issues.

In discussing the results of this paper, the authors would like to acknowledge certain limitations. In this paper, we followed a semi-systematic review method (Roy et al., 2021) because we used only one literature database—Scopus, and performed a focused search on Google Scholar with only English language articles included. As mentioned in Roy et al. (2021) and Sovacool et al. (2018), conducting a full systematic review is time consuming which only focuses on narrow range of research question and prevents in-depth analysis. From the Scopus search, it is found that studies are conspicuously biased towards developed countries (~88% - 111 out of 126 articles mentioning single-country names). Future studies could potentially explore country focused search with varying search terms, try to look for non-English language studies to capture diverse national contexts to bring out regional studies. Despite this limitation and the inadvertent bias arising mostly from developed country-based studies, the strength of this paper lies in that this is the first study that tries to look at how the interventions associated with reducing consumer food waste and sustainable dietary choices can be categorised under A-S-I framework, classifying each intervention by social actors responsible to help in implementation or scaling up. Moreover, this paper assesses the links at the SDG level and reports the associated SDG targets (SM4). Future studies can take a deeper look going beyond qualitative SDG link analysis, and quantifying the SDG links which will be helpful in understanding the magnitude of sustainable lifestyle these two mitigation options can provide, and could also focus on specific SDG targets and indicators relevant for local contexts to derive targeted actions/policies. A detailed context specific barrier analysis will be helpful in speeding up actions. Food waste related interventions can also be considered within various circular economy concepts using waste hierarchy which has not been attempted in this paper.

This research has answered some questions but has given rise to many other possible questions for future research. Some of these are (1) what infrastructural support is needed for reducing food waste in both upstream (through supply chain partner) and downstream (recycling, reusing at consumer end) in low and middle income countries v/s high income countries; (2) what soft or hard infrastructural, technological and economic supports are needed for changing dietary choices towards balanced, sustainable healthy diets featuring less meat for meat exporting countries v/s importing countries; (3) understanding of socio-cultural, attitudinal, normative and behavioural differences regarding food waste and dietary choices among people classified by income groups and various other social stratification within and across countries; (4) how drivers of behavioural, lifestyle and socio-cultural changes have been theoretically addressed for these two mitigation options, in various disciplinary approaches and what complementary or commonality can be found; (5) assessing the links at the SDG targets and the SDG indicators levels, (6) quantification of rebound effects; (7) how to measure/determine effectiveness of the 92 interventions identified in different context; (8) identifying barriers in implementation of 92 interventions in various contexts; (9) understanding the long-term impacts of these interventions to figure out their durability in changing behaviour as sustained behaviour change is needed to shift towards a sustainable consumption system; (10) understanding the influence of marketing, social media and mass media on behavioural and lifestyle choices of consumers, and exploring the potential of social and behaviour change communication-campaigns in shifting consumer attitude, norms and behaviour; (11) understanding the influence of social media and mass media on supply chain partners (supermarkets, eateries) who play an pivotal role towards enabling and promoting sustainable dietary choices.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used are provided in the manuscript and the five supplementary materials

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.133432.

References

Alsaffar, A.A., 2016. Sustainable diets: the interaction between food industry, nutrition, health and the environment. Food Sci. Technol. Int. 22 (2), 102–111. https://doi.org/10.1177/1082013215572029.

Armstrong Soule, C.A., Sekhon, T., 2019. Preaching to the middle of the road. Br. Food J. 121 (1), 157–171. https://doi.org/10.1108/bfj-03-2018-0209.

Bajželj, B., Richards, K., Allwood, J., Smith, P., Dennis, J., Curmi, E., Gilligan, C., 2014. Importance of food-demand management for climate mitigation. Nat. Clim. Change 4 (10), 924–929.

Banerjee, S., John, P., 2021. Nudge plus: incorporating reflection into behavioral public policy. Behave Pub. Pol. 1–16. https://doi.org/10.1017/bpp.2021.6.

Benyam, A., Kinnear, S., Rolfe, J., 2018. Integrating community perspectives into domestic food waste prevention and diversion policies. Resour. Conserv. Recycl. 134 (March), 174–183. https://doi.org/10.1016/j.resconrec.2018.03.019.

Boulding, P., Patrik, E., Brüggemann, N., Timmermans, A.J.M., Cseh, B., de Riez, R., 2019. Evaluation Framework for Action Innovation Projects: A Series of Case Studies from Germany, The Netherlands, Hungary and Spain (REFRESH).

Chakravarty, D., Dasgupta, S., Roy, J., 2013. Rebound effect: how much to worry? Curr. Opin. Environ. Sustain. 5 https://doi.org/10.1016/j.cosust.2013.03.001, 2013.

Charlebois, S., McCormick, M., Juhasz, M., 2016. Meat consumption and higher prices: discrete determinants affecting meat reduction or avoidance amidst retail price volatility. Br. Food J. 118 (9), 2251–2270. https://doi.org/10.1108/BFJ-03-2016-0121.

Conrad, Z., Niles, M.T., Neher, D.A., Roy, E.D., Tichenor, N.E., Jahns, L., 2018. Relationship between food waste, diet quality, and environmental sustainability. PLoS One 13 (4), 1–18. https://doi.org/10.1371/journal.pone.0195405.

Creutzig, F., Callaghan, M.W., Ramakrishnan, A., Javaid, A., Niamir, L., Müller-Hansen, F., et al., 2020. 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. https://doi.org/10.1088/1748-9326/abd78b.

Creutzig, F., Roy, J., Devine-Wright, P., Díaz-José, J., Geels, F.W., Grubler, A., Maïzi, N., Masanet, E., Mulugetta, Y., Onyige, C.D., Perkins, P.E., Sanches-Pereira, A., Weber, E.U., et al., 2022. Demand, services and social aspects of mitigation. In: Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J. (Eds.), IPCC, 2022*: Climate Change 2022: Mitigation Of Climate Change. Contribution Of Working Group III to the Sixth Assessment Report Of the Intergovernmental Panel On Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.007.

Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M., Bruin, W.B., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. Nat. Clim. Change 8 (4), 268.

Culliford, A., Bradbury, J., 2020. A cross-sectional survey of the readiness of consumers to adopt an environmentally sustainable diet. Nutr. J. 19 (1), 1–13. https://doi.org/10.1186/s12937-020-00644-7.

de Boer, J., Aiking, H., 2017. Pursuing a low meat diet to improve both health and sustainability: how can we use the frames that shape our meals? Ecol. Econ. 142, 238–248. https://doi.org/10.1016/j.ecolecon.2017.06.037.

Dhiman, S., 2018. To eat or not to eat meat: striking at the root of global warming. In: Handbook of Engaged Sustainability, pp. 37–62. Retrieved from. http://webcache.googleusercontent.com/search?q=cache:njrMOHYJ9L8J:reading.buddhistdoor.com/resources/get/7198bed116ce035d4535a5ab409724b5da23893c+&cd=9&hl=en&ct=clnk&gl=ch&client=firefox-a.

Duarte, M., Vasconcelos, M., Pinto, E., 2020. Pulse consumption among Portuguese adults: potential drivers and barriers towards a sustainable diet. Nutrients 12 (11), 3336. https://doi.org/10.3390/nu12113336.

Ethridge, D., 1973. The inclusion of wastes in the theory of the firm. J. Polit. Econ. 81 (6), 1430–1441.

Eker, S., Reese, G., Obersteiner, M., 2019. Modelling the drivers of a widespread shift to sustainable diets. Nat. Sustain. 2 (8), 725–735. https://doi.org/10.1038/s41893-019-0331-1.

FAO, 2020. Food-based-dietary guidelines. Available online: http://www.fao.org/nutrition/nutrition-education/food-dietary-guidelines/en/. (Accessed 14 May 2020).

FAO, 2011. Global food losses and food waste – extent, causes and prevention. Available online: http://www.fao.org/3/i2697e/i2697e.pdf. (Accessed 14 May 2021).

Fischedick, M., Roy, J., et al., 2014. Industry. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), *Climate Change 2014: Mitigation Of Climate Change. Contribution Of Working Group III to the Fifth Assessment Report Of the Intergovernmental Panel On Climate Change*. Cambridge University Press.

Filimonau, V., Fidan, H., Alexieva, I., Dragoev, S., Marinova, D.D., 2019. Restaurant food waste and the determinants of its effective management in Bulgaria: an exploratory case study of restaurants in Plovdiv. Tourism Manag. Perspect. 32, 100577 https://doi.org/10.1016/j.tmp.2019.100577.

Filimonau, V., Delysia, A., 2019. Food waste management in hospitality operations: a critical review. Tourism Manag. 71, 234–245. https://doi.org/10.1016/j.tourman.2018.10.009.

Frank, S., Gusti, M., Havlík, P., Lauri, P., DiFulvio, F., Forsell, N., et al., 2021. Land-based climate change mitigation potentials within the agenda for sustainable development. Environ. Res. Lett. 16 (2), 024006. https://iopscience.iop.org/article/10.1088/1748-9326/abc58a.

García-González, Á., Achón, M., Carretero Krug, A., Varela-Moreiras, G., Alonso-Aperte, E., 2020. Food sustainability knowledge and attitudes in the Spanish adult population: a cross-sectional study. Nutrients 12 (10), 3154. https://doi.org/10.3390/nu12103154.

Georgescu-Roegen, N., 1971. The entropy law and the economic process. In: The Entropy Law and the Economic Process. Harvard university press.

Goodman-Smith, F., Mirosa, R., Mirosa, M., 2020. Understanding the effect of dining and motivational factors on out-of-home consumer food waste. Sustainability 12 (16), 6507. https://doi.org/10.3390/su12166507.

Goldstein, B., Moses, R., Sammons, N., Birkved, M., 2017. Potential to curb the environmental burdens of American beef consumption using a novel plant-based beef substitute. PLoS One 12 (12), 1–17. https://doi.org/10.1371/journal.pone.0189029.

González-García, S., Esteve-Llorens, X., Moreira, M.T., Feijoo, G., 2018. Carbon footprint and nutritional quality of different human dietary choices. Sci. Total Environ. 644, 77–94. https://doi.org/10.1016/j.scitotenv.2018.06.339.

Green, M., Leonard, R., Malkin, S., 2018. Organisational responses to climate change: do collaborative forums make a difference? Geogr. Res. 56 (3), 311–324. https://doi.org/10.1111/1745-5871.12286.

Haddaway, N.R., Woodcock, P., Macura, B., Collins, A., 2015. Making literature reviews more reliable through application of lessons from systematic reviews. Conserv. Biol. 29 (6), 1596–1605.

Halldórsdóttir, P.Ó., Nicholas, K.A., 2016. Local food in Iceland: identifying behavioral barriers to increased production and consumption. Environ. Res. Lett. 11 (11) https://doi.org/10.1088/1748-9326/11/11/115004.

Hallström, E., Carlsson-Kanyama, A., Börjesson, P., 2015. Environmental impact of dietary change: a systematic review. J. Clean. Prod. 91, 1–11. https://doi.org/10.1016/j.jclepro.2014.12.008.

Hallström, E., Bergman, K., Mifflin, K., Parker, R., Tyedmers, P., Troell, M., Ziegler, F., 2019. Combined climate and nutritional performance of seafoods. J. Clean. Prod. 230, 402–411. https://doi.org/10.1016/j.jclepro.2019.04.229.

Hanley, N., Shogren, J.F., White, B., 1997. Environmental Economics in Theory and Practice. Palgrave Macmillan.

Hoek, A.C., Pearson, D., James, S.W., Lawrence, M.A., Friel, S., 2017. Shrinking the food-print: a qualitative study into consumer perceptions, experiences and attitudes towards healthy and environmentally friendly food behaviours. Appetite 108, 117–131. https://doi.org/10.1016/j.appet.2016.09.030.

Hoegh-Guldberg, O., et al., 2019. The Ocean as a Solution to Climate Change: Five Opportunities for Action. Report. Washington, DC. World Resources Institute. Available online at. http://www.oceanpanel.org/climate.

Honegger, M., Michaelowa, A., Roy, J., 2021. Potential implications of carbon dioxide removal for the sustainable development goals. Clim. Pol. 21 (5), 678–698. https://doi.org/10.1080/14693062.2020.1843388.

IPCC, 2019. Summary for policymakers. In: Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (Eds.), Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems (in press).

IPCC, 2022. Summary for policymakers. In: Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J. (Eds.), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA (in press). https://dx.doi.org/10.48490/f0z3-n524. (Accessed 4 April 2022).

Jackson, R.B., Ahlström, A., Hugelius, G., Wang, C., Porporato, A., Ramaswami, A., et al., 2022. Human well-being and per capita energy use. Ecosphere 13 (4), e3978. https://doi.org/10.1002/ecs2.3978.

Jalava, M., Guillaume, J.H.A., Kummu, M., Porkka, M., Siebert, S., Varis, O., 2016. Diet change and food loss reduction: what is their combined impact on global water use and scarcity? Earth's Future 4 (3), 62–78. https://doi.org/10.1002/2015EF000327.

Jensen, J.D., Saxe, H., Denver, S., 2015. Cost-effectiveness of a new nordic diet as a strategy for health promotion. Int. J. Environ. Res. Publ. Health 12 (7), 7370–7391. https://doi.org/10.3390/ijerph120707370.

Kaljonen, M., Salo, M., Lyytimäki, J., Furman, E., 2020. From isolated labels and nudges to sustained tinkering: assessing long-term changes in sustainable eating at a lunch restaurant. Br. Food J. https://doi.org/10.1108/BFJ-10-2019-0816.

Kwasny, T., Dobernig, K., Riefler, P., 2022. Towards reduced meat consumption: a systematic literature review of intervention effectiveness. Appetite 168, 105739. https://doi.org/10.1016/j.appet.2021.105739, 2001–2019.

Lindgren, E., Harris, F., Dangour, A.D., Gasparatos, A., Hiramatsu, M., Javadi, F., et al., 2018. Sustainable food systems—a health perspective. Sustain. Sci. 13 (6), 1505–1517. https://doi.org/10.1007/s11625-018-0586-x.

④ Asian Institute of Technology (AIT)

Lorenz, S., Porter, J.J., Dessai, S., 2019. Identifying and tracking key climate adaptation actors in the UK. Reg. Environ. Change 19 (7), 2125–2138. https://doi.org/10.1007/s10113-019-01551-2.

Lorenz-Walther, B.A., Langen, N., Göbel, C., Engelmann, T., Bienge, K., Speck, M., Teitscheid, P., 2019. What makes people leave LESS food? Testing effects of smaller portions and information in a behavioral model. Appetite 139, 127–144. https://doi.org/10.1016/j.appet.2019.03.026. March 2018.

Lynch, H., Johnston, C., Wharton, C., 2018. Plant-based diets: considerations for environmental impact, protein quality, and exercise performance. Nutrients 10 (12), 1–16. https://doi.org/10.3390/nu10121841.

Malek, L., Umberger, W., Goddard, E., 2019. Is anti-consumption driving meat consumption changes in Australia? Br. Food J. 121 (1), 123–138. https://doi.org/10.1108/BFJ-03-2018-0183.

Manzocco, L., Alongi, M., Sillani, S., Nicoli, M.C., 2016. Technological and consumer strategies to tackle food wasting. Food Eng. Rev. 8 (4), 457–467. https://doi.org/10.1007/s12393-016-9149-z.

Marques, A.C., Fuinhas, J.A., Pais, D.F., 2018. Economic growth, sustainable development and food consumption: evidence across different income groups of countries. J. Clean. Prod. 196, 245–258. https://doi.org/10.1016/j.jclepro.2018.06.011.

Marshall, D., Bano, F., Banas, K., 2022. A meaty issue: the effect of meat-related label terminology on the willingness to eat vegetarian foods. Food Qual. Prefer. 96, 104413 https://doi.org/10.1016/j.foodqual.2021.104413.

Martins, L.M., Rodrigues, S.S., Cunha, L.M., Rocha, A., 2016. Strategies to reduce plate waste in primary schools - experimental evaluation. Publ. Health Nutr. 19, 1517–1525. https://doi.org/10.1017/S1368980015002797.

Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., et al., 2010. *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Intergovernmental Panel on Climate Change, Geneva (IPCC). https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf.

Available online: Meatless Mondays www.meatlessmonday.com. (Accessed 20 October 2019).

Morone, P., Falcone, P.M., Lopolito, A., 2019. How to promote a new and sustainable food consumption model: a fuzzy cognitive map study. J. Clean. Prod. 208, 563–574. https://doi.org/10.1016/j.jclepro.2018.10.075.

Mu'azu, N.D., Blaisi, N.I., Naji, A.A., Abdel-Magid, I.M., AlQahtany, A., 2019. Food waste management current practices and sustainable future approaches: a Saudi Arabian perspective. J. Mater. Cycles Waste Manag. 21 (3), 678–690. https://doi.org/10.1007/s10163-018-0808-4.

Nilsson, M., Griggs, D., Visback, M., 2016. Map the interactions between sustainable development goals. Nature 534 (7607), 320–322. https://doi.org/10.1038/534320a.

Orkusz, A., Wolańska, W., Harasym, J., Piwowar, A., Kapelko, M., 2020. Consumers' attitudes facing entomophagy: polish case perspectives. Int. J. Environ. Res. Publ. Health 17 (7), 2427. https://doi.org/10.3390/ijerph17072427.

Papargyropoulou, E., Lozano, R., Steinberger, J.K., Wright, N., bin Ujang, Z., 2014. The food waste hierarchy as a framework for the management of food surplus and food waste. J. Clean. Prod. 76, 106–115. https://doi.org/10.1016/j.jclepro.2014.04.020.

Pathak, M., Slade, R., Shukla, P.R., Skea, J., Pichs-Madruga, R., Ürge-Vorsatz, D., 2022. Technical summary. In: Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J. (Eds.), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.002.

Peltola, T., Kaljonen, M., Kettunen, M., 2020. Embodied public experiments on sustainable eating: demonstrating alternative proteins in Finnish schools. Sustain. Sci. Pract. Pol. 16 (1), 184–196. https://doi.org/10.1080/15487733.2020.1789268.

Pinto, R.S., Pinto, R.M., dos, S., Melo, F.F.S., Campos, S.S., Cordovil, C.M., dos, S., 2018. A simple awareness campaign to promote food waste reduction in a University canteen. Waste Manag. 76, 28–38. https://doi.org/10.1016/j.wasman.2018.02.044, 2018.

Reynolds, C., Goucher, L., Quested, T., Bromley, S., Gillick, S., Wells, V.K., et al., 2019a. Review: consumption-stage food waste reduction interventions – what works and how to design better interventions. Food Pol. 83 (January), 7–27. https://doi.org/10.1016/j.foodpol.2019.01.009.

Reynolds, C.J., Horgan, G.W., Whybrow, S., Macdiarmid, J.I., 2019b. Healthy and sustainable diets that meet greenhouse gas emission reduction targets and are affordable for different income groups in the UK. Publ. Health Nutr. 22 (8), 1503–1517. https://doi.org/10.1017/S1368980018003774.

Röös, E., Carlsson, G., Ferawati, F., Hefni, M., Stephan, A., Tidåker, P., Witthöft, C., 2018. Less meat, more legumes: prospects and challenges in the transition toward sustainable diets in Sweden. Renew. Agric. Food Syst. https://doi.org/10.1017/S1742170518000443.

Rosenzweig, C., Mbow, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M., et al., 2020. Climate change responses benefit from a global food system approach. Nature Food 1 (2), 94–97.

Roy, J., Dowd, A.-M., Muller, A., Pal, S., Prata, N., 2012. Chapter 21 - lifestyles, well-being and energy. In: Global Energy Assessment - toward a Sustainable Future. Cambridge University Press, pp. 1527–1548. Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Roy, J., Pal, S., 2009. Lifestyles and climate change: link awaiting activation. Curr. Opin. Environ. Sustain. 1 (2), 192–200.

Roy, J., Some, S., Das, N., Pathak, M., 2021. Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abd81a.

Roy, J., Tschakert, P., et al., 2018. Sustainable development, poverty eradication and reducing inequalities supplementary material. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, R.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), *Global Warming of 1.5°C. A 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*. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 445–538. https://www.ipcc.ch/sr15/chapter/chapter-5/.

Rust, N.A., Ridding, L., Ward, C., Clark, B., Kehoe, L., Dora, M., et al., 2020. How to transition to reduced-meat diets that benefit people and the planet. Sci. Total Environ. 718, 137208 https://doi.org/10.1016/j.scitotenv.2020.137208.

Ruzgys, S., Pickering, G.J., 2020. Perceptions of cultured meat among youth and messaging strategies. Front. Sustain. Food Syst. 4, 122. https://doi.org/10.3389/fsufs.2020.00122.

Sahakian, M., Godin, L., Courtin, I., 2020. Promoting 'pro','low', and 'no'meat consumption in Switzerland: the role of emotions in practices. Appetite 150, 104637. https://doi.org/10.1016/j.appet.2020.104637.

Saunders, H.D., Roy, J., et al., 2021. Energy Efficiency: what has research delivered in the last 40 years? Annu. Rev. Environ. Resour. 46, 135–165. https://www.annualreviews.org/doi/pdf/10.1146/annurev-environ-012320-084937.

Schanes, K., Dobernig, K., Gözet, B., 2018. Food waste matters - a systematic review of household food waste practices and their policy implications. J. Clean. Prod. 182, 978–991. https://doi.org/10.1016/j.jclepro.2018.02.030.

Schenk, P., Rössel, J., Scholz, M., 2018. Motivations and constraints of meat avoidance. Sustainability 10 (11), 1–19. https://doi.org/10.3390/su10113858.

Schwartz, M.B., Henderson, K.E., Read, M., Danna, N., Ickovics, J.R., 2015. New school meal regulations increase fruit consumption and do not increase total plate waste. Child. Obesity 11, 242–247. https://doi.org/10.1089/chi.2015.0019.

Secondi, L., Principato, L., Mattia, G., 2020. Can digital solutions help in the minimization of out-of-home waste? An analysis from the client and business perspective. Br. Food J. https://doi.org/10.1108/BFJ-03-2019-0205.

Shepon, A., Eshel, G., Noor, E., Milo, R., 2018. The opportunity cost of animal based diets exceeds all food losses. Proc. Natl. Acad. Sci. U.S.A. 115 (15), 3804–3809. https://doi.org/10.1073/pnas.1713820115.

Some, S., 2020. Exploring mitigation interventions and SDGs link: evidences from Indian agriculture. In: Diemer, A., et al. (Eds.), Paradigms, Models, Scenarios and Practices for Strong Sustainability. Clermont-Ferrand: Editions Oeconomia, pp. 339–356. https://usercontent.one/wp/www.erasmecentre.eu/wp-content/uploads/2021/03/strongsustainabilitybook.pdf, 979-10-92495-13-3.

Sovacool, B.K., Axsen, J., Sorrell, S., 2018. Promoting novelty, rigor, and style in energy social science: towards codes of practice for appropriate methods and research design. *Energy Res. Social Sci*. 45, 12. https://doi.org/10.1016/j.erss.2018.07.007. –42.

Supartini, A., Oishi, T., Yagi, N., 2018. Changes in fish consumption desire and its factors: a comparison between the United Kingdom and Singapore. Foods 7 (7), 97. https://doi.org/10.3390/foods7070097.

Taufik, D., 2018. Prospective "warm-glow" of reducing meat consumption in China: emotional associations with intentions for meat consumption curtailment and consumption of meat substitutes. J. Environ. Psychol. 60 (April), 48–54. https://doi.org/10.1016/j.jenvp.2018.10.004.

Trewern, J., Chenoweth, J., Christie, I., 2022. Sparking Change: evaluating the effectiveness of a multi-component intervention at encouraging more sustainable food behaviors. Appetite 171, 105933. https://doi.org/10.1016/j.appet.2022.105933.

Ürge-Vorsatz, D., Herrero, S.T., Dubash, N.K., Lecocq, F., 2014. Measuring the co-benefits of climate change mitigation. Annu. Rev. Environ. Resour. 39, 549–582.

USDA, 2019. ChooseMyPlate. Available online: http://www.choosemyplate.gov. (Accessed 29 June 2019).

van Dooren, C., Keuchenius, C., de Vries, J.H.M., de Boer, J., Aiking, H., 2018. Unsustainable dietary habits of specific subgroups require dedicated transition strategies: evidence from The Netherlands. Food Pol. 79 (May), 44–57. https://doi.org/10.1016/j.foodpol.2018.05.002.

van Herpen, E., De Hooge, I.E., de Visser-Amundson, A., Kleijnen, M.P., 2021. Take it or leave it: how an opt-out strategy for doggy bags affects consumer food waste behavior and restaurant evaluations. J. Clean. Prod. 325, 129199 https://doi.org/10.1016/j.jclepro.2021.129199.

Varela, P., Arvisenet, G., Gonera, A., Myhrer, K.S., Fifi, V., Valentin, D., 2022. Meat replacer? No thanks! The clash between naturalness and processing: an explorative study of the perception of plant-based foods. Appetite 169, 105793. https://doi.org/10.1016/j.appet.2021.105793.

Vásquez, J.M., Cequea, M.M., Schmitt, V.G.H., Ferasso, M., 2022. Food consumption and food waste behaviour in households in the context of the COVID-19 pandemic. Br. Food J. https://doi.org/10.1108/BFJ-07-2021-0798.

von Kameke, C., Fischer, D., 2018. Preventing household food waste via nudging: an exploration of consumer perceptions. J. Clean. Prod. 184, 32–40. https://doi.org/10.1016/j.jclepro.2018.02.131.

West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K.A., Carlson, K.M., et al., 2014. Leverage points for improving global food security and the environment. Science 345 (6194), 325–328.

④ Asian Institute of Technology (AIT)

Young, W., Russell, S.V., Robinson, C.A., Barkemeyer, R., 2017. Can social media be a tool for reducing consumers' food waste? A behaviour change experiment by a UK retailer. Resour. Conserv. Recycl. 117, 195–203. https://doi.org/10.1016/j.resconrec. 2016.10.016.

Yu, E., Malik, V.S., Hu, F.B., 2018. Reprint of: cardiovascular disease prevention by diet modification. J. Am. Coll. Cardiol. 72 (23), 2951–2963. https://doi.org/10.1016/j.jacc.2018.10.019.

Żakowska-Biemans, S., Pieniak, Z., Kostyra, E., Gutkowska, K., 2019. Searching for a measure integrating sustainable and healthy eating behaviors. Nutrients 11 (1), 1–17. https://doi.org/10.3390/nu11010095.

Zeng, T., Durif, F., 2020. The impact of eco-design packaging on food waste avoidance: a conceptual framework. J. Promot. Manag. 26 (5), 768–790. https://doi.org/10.1080/10496491.2020.1729320.

Zhang, H., Duan, H., Andric, J.M., Song, M., Yang, B., 2018. Characterization of household food waste and strategies for its reduction: a Shenzhen City case study. Waste Manag. 78, 426–433. https://doi.org/10.1016/j.wasman.2018.06.010.

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Annex IV



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GP-ORF Series

Sustainable Development in Action: Examining Global North-South Divergences

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10

E-Mobility for a Sustainable World: Unavoidable Automobility and Global South-North Perspectives

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People and freight movement accounts for 15 percent of global greenhouse gas emissions (1). Not all mobility or even automobility demand can be fully avoided as it is the mobility service that connects the point of demand and point of supply in an interdependent modern human society (see Figure 1 and Table 1). It is important then to consider how unavoidable automobility (mobility necessary to access services essential for human living) can be promoted bearing in mind the Sustainable Development Goals (SDGs), particularly SDG 7 (ensure access to affordable, reliable, sustainable and modern energy for all) and SDG 13 (take urgent action to combat climate change and its impacts) (2). Policymakers, spatial planners and service-delivery providers are the key actors to introduce any change related to mobility services, supplemented by information sharing to enhance user awareness and shape user behaviour (3). While digitalisation, information and communication, and interactive technologies may help in reimagining mobility services (4) their influence on the impact of mobility and energy demand on the environment is yet to be assessed (5).

Mobility is not just for the physical transportation of passengers but for goods as well. Societies with a high interdependence through import-export of goods lead to an increased demand for automobility. Importantly, 90 percent of all global freight movement is by ships that run on fossil fuels (6).

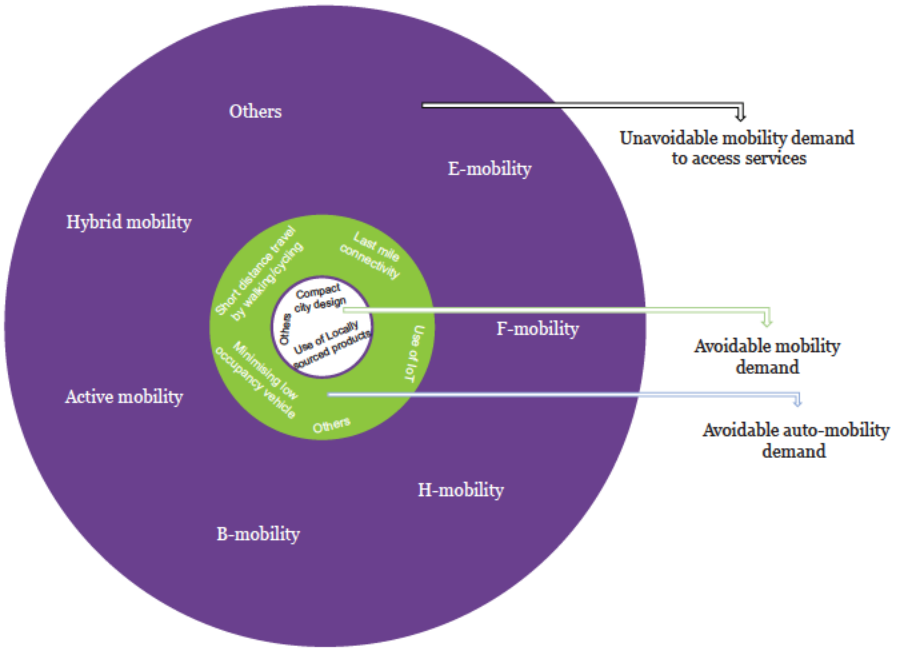
North-South Binary

Existing literature on collective sustainable living (7) and eco-modern justice (8) highlights the need for mainstream research to go beyond traditional binary representations to show equity, such as North-South, rich-poor, developed-developing, or Annex I- Non-Annex I countries. The north-south binary, which emerged amid globalisation from traditional political economy literature (9), trade

literature (10), and geography (11), needs to be reframed in the wake of the global sustainability discourse and different economic levels across social groups. This paper views the Global South and North not as geographic regions but as 'social designations' for vulnerable communities due to political-social-economic factors in rich and poor countries (12).

Social inequity in mobility is connected to levels of wealth, poverty and capabilities. People with a lower level of travel demand may satisfy one or a combination of the following factors: unemployment, low income, have a low ownership of vehicles, live in settlements that are less served by modern travel modes and services, have a lower capability to join the skilled labour market (13), and lack decent living standards (14). This group with a mobility deficit or deprivation will vary depending on the level of equity and inequity within a country. Unlike cooking fuel use, which leads to biomass burning and has environmental impacts, the mobility of a poor social group can typically be categorised under active mobility service and hence has a minimal contribution to the environment (Global South perspective). This paper focuses on unavoidable automobility, or the Global North perspective that cuts across all countries.

Figure 1: Avoidable and Unavoidable Mobility Demand



Source: Conceptualised by authors based on J.Roy et al, and B. Ghosh (15)

Reimagining Mobility

E-mobility emerged as a supply-side option in low emission mobility solutions under the assumption that electricity supply can be from zero carbon sources (see Figure 1). The sustainable development framework, digitalisation, Big Data and internet of things (IoT) (16), provide an opportunity to reimagine the mobility of people and goods in a broader context, with the potential for new investment in infrastructure, service provision systems (17), and an overall enabling environment through policy incentives without compromising on human wellbeing or breaking sectoral boundaries.

Transforming service provision systems: Avoiding demand for mobility

Avoiding mobility is not an option for the Global South as such communities are already living with unmet mobility demands and low levels of wellbeing. It is, however, applicable to the Global North communities that are directly or indirectly dependent on automobility and unavoidable automobility; they are the major driver of global unavoidable demand for automobility.

Infrastructure design and promoting it appropriately as a "new normal status symbol" will play an important role in avoiding the demand for mobility. For instance, compact urban planning will help in avoiding mobility (18). Mobility service provision through collaborative mobility demand (19), and reducing vehicle ownership by increasing the occupancy of vehicles by increasing comfort in public transport system (20) helps avoid and reduce mobility demand. Cities that are experiencing growth and are developing their infrastructure have the potential to incorporate plans and designs to encourage low mobility, and thus low energy, demand.

Active mobility for a sustainable world

The Global South is mostly dependent on active mobility that is sustainable but is trapped at a low level of human wellbeing without access to opportunities. However, for the Global North, active mobility is now emerging as an alternative sustainable option to enhance human wellbeing for certain services that are available at short distances and thus provide healthy options and reduce emissions through modern digital and physical infrastructure design (21).

The purpose of mobility can be varied (see Table 1). Active mobility through walking or cycling has no direct adverse environmental emissions since no fuel is used, and so is perfectly compatible with sustainable mobility. The mobility of people and goods

can be over a short, intermediate or long distance. Typically, active travel is for short distances, and motorised mobility is for long-distance travel.

Mobility can be to maintain various needs, such as accessing educational spaces or workplaces, entertainment and shopping, healthcare, leisure and tourism, and socialisation. Often, the movement of people and goods can be complementary or substitutes, providing scope to avoid the mobility need of one kind or the other (see Table 1). Digitalisation and IoT are transforming the service provision system and increasing substitutability in passenger and freight movements. For instance, online food ordering, telecommuting for work, online shopping, and E-education. One way of measuring progress in sustainability is the status of human health (a component

Table 1: Means for Mobility

Transport types	Physical movement			
	People (passenger km)		Freight (ton km)	
	Global growth rates over the period*			
Active transport	Not available		Not available	
Road transport	193.17% (2000-2017)		100% (1990-2003)	
Rail transport	16.27% (1995-2007)		20.13% (1995-2010)	
Air transport	1368.11% (1970-2019)#		1322.70% (1973-2019)	
Water transport	Not available		120% (1990-2003)	
Purpose (Distance to cover)	**Private**	**Shared**	**Domestic**	**International**
Short	Active mobility: Walk, Cycle/bike Automobility: 2W, 3W, 4W	Active mobility: Cycle/bike Automobility: 2W, 3W, 4W	Active mobility: Walk, Cycle/bike Automobility: 2W, 3W, 4W	Train, Bus, Airplane, Ship
Intermediate	Active mobility: Cycle/bike Automobility: 2W, 3W, 4W	Active mobility: Cycle/bike Automobility: 2W, 3W, 4W, Bus	Active mobility: Cycle/bike Automobility: 2W, 3W, 4W	Train, Bus, Airplane, Ship
Long	4W	4W, Train, Metro, Bus, Airplane, Ship	3W, 4W, Train, Bus, Airplane, Ship	Train, Bus, Airplane, Ship
Access to Services	**Physical movement (of people)**	**Digitalised platforms**	**Physical movement (of freight)**	
Education	High potential for reduction	High potential for increase	Marginal/No additional physical movement of freight needed	
Job	High potential for reduction	High potential for increase	Marginal/No additional physical movement of freight needed	
Entertainment services (opera/ movies/sports)	High potential for reduction	High potential for increase	No additional physical movement of freight needed	
Dine out	High potential for reduction	High potential for increase	Potential for some additional physical movement of freight needed	
Bank/ATM	Medium potential for reduction	Medium potential for increase	No additional physical movement of freight needed	
Shopping	Medium potential for reduction	Medium potential for increase	Should be complemented by physical movement of freight	
Salon	Medium potential for reduction	Medium potential for increase	Additional physical movement of freight may not be necessary	
Health	Low potential for reduction	Low potential for increase	Should be complemented by physical movement of freight	
Leisure activities (gym/ swimming etc.)	No potential for reduction	No potential for increase	No additional physical movement of freight needed	
Parties (outside house)	No potential for reduction	No potential for increase	No additional physical movement of freight needed	

Note: #Total passengers carried
High potential: when services can be ordered/ booked online but no physical movement of people necessary to deliver the product/services
Medium potential: when services can be ordered/ booked online but physical movement of people necessary to deliver the product/services
Low potential: when only few options under the broader umbrella of services (e.g., health) can be ordered/ booked online

Source: Compiled by authors. *Calculated from World Bank and Global Energy Assessment (26)

of multidimensional metrics used to measure human wellbeing) (22). Studies show life-cycle CO_2 emission reduced by 14 percent with each additional cycle trip and by 62 percent with each avoided car trip (23). But such a shift in active mobility is determined by the availability of and access to infrastructure. Active mobility cannot happen in an urban centre if the city is not walkable by design (24). Thus, the overall demand for mobility might decline if managed strategically. But unless well-managed, it can lead to an increase in energy use and emissions as well (25).

Table 2: Adoption of E-Vehicles by Types

E-vehicle types	Implementation in countries
E-bike (2W)	China (27)
E-rickshaw (3W)	India (28)
E-cars (4W)	Norway, Iceland, Sweden, Finland (29)
E-buses	China, India (30)
E-trucks (freight)	US (31)
Electric trains/ metros/ underground rails	Hamburg (Germany) (32)
Electric cruise boats	US, South Korea (33)
Electric tram	Kolkata, Mumbai (India) (34)

Source: Compiled by the authors

E-mobility for Unavoidable Mobility in a Sustainable World

How can unavoidable mobility needs be met in a sustainable world, immediately for the Global North and expanded in the future for the entire population? E-mobility, H-mobility (hydrogen fuel-driven mobility) and B-mobility (biofuel-driven mobility) can be the solution. The rise in the use of lithium-ion batteries has enabled E-mobility to become a major feature of decarbonisation (see Table 2).

In light duty vehicles, E-mobility through fully battery-operated vehicles instead of internal combustion engines are becoming a commercial reality faster than anticipated across the globe (35). This is due to changes in national policies, vehicle manufacturing companies adopting new business ventures, business prospects evolving due to change in company valuation, and innovation in mobility technologies (see Table 3).

In India, initiatives such as a massive expansion of metro-rail networks in multiple cities are promoting E-mobility. Rising liquid fuel costs and the ban on two-stroke

engines are some of the factors that have driven a quicker e-mobility transition in India (36). Bangalore Metropolitan Transport Corporation (BMTC) provides feeder bus services to and from metro railway stations to ease the continuity of the mobility service. BMTC has also planned to provide electric bikes at five metro stations. A number of other experimentations that are being introduced, include bus rapid transit systems (Ahmedabad, Pune, Kolkata), electric rickshaws (New Delhi, Kolkata and various other cities), promotion of different modes of non-motorised transport (Bhubaneshwar, Ahmedabad).

In developing countries, E-mobility is being rapidly implemented in micro-mobility (E-autorickshaws, scooters, E-bikes), in transit systems (especially buses) and, to a lesser degree, in the electrification of personal vehicles through various E-mobility policies (see Table 3for policies in South Asian countries). India's large and growing two-wheeler market has benefitted from the policy attention on electric vehicles (EVs), showing a significant potential for increasing the share of electric two-and three-wheelers in the short term (37). Similar opportunities exist for China where e-bikes have replaced car trips and are reported to act as intermediate links in multimodal mobility (38). China's EV market grew by 118 percent in the first quarter of 2019 (see Table 2a) and is currently larger than the EU and the US combined (39). In Chile, as of 2014, only 136 vehicles (0.003% of the total fleet) are electricity-fuelled (40). It is also important for innovation and service delivery providers to provide adequate charging points to support the penetration of EVs. In Brazil, the Itaipu hydroelectric power plant has established an electric car sharing platform for its employees (41).

Table 3: Emerging E-mobility Policies in South Asian

Country	E-mobility policy	Targets/ Incentives
Afghanistan	No EV policy yet	-
Bangladesh (42)	Automobile Industry Development Policy 2021	10-year tax holiday, financial incentives, interest waiver on loans for local manufacturing and assembly of EVs. Global Environment Facility (GEF) announced plans to help Bangladesh accelerate their shift to zero-emissions electric mobility (in Nov 2021) Bangladesh Road Transport Corporation (BRTC) has taken the initiative to introduce 50 electric buses that will run in long routes like Dhaka-Chottogram.

Country	E-mobility policy	Targets/ Incentives
Bhutan (43)	Bhutan Electric Vehicle Initiative (2014)	To make the capital city, Thimphu, a clean Green Electric City Promotes EVs with tax incentives. EVs are exempt from sales tax, customs duty, and green tax. The country has an EV initiative including a GEF project for electric taxis. It has also discussed an EV road map for commercial vehicles (buses, urban trucks, and taxis)
India (44)	National Electric Mobility Mission Plan FAME II (April 2019 for 3 years)- Faster Adoption and Manufacturing of (Hybrid and) Electric Vehicles Phase II	Ensure at least 15% of the vehicles in the country are electric by 2030 The scheme is proposed to be implemented through the following verticals: a) Demand Incentives (upfront reduced purchase price of hybrid and electric vehicles to enable wider adoption, which will be reimbursed to the original equipment manufacturer by the Indian government) b) Establishment of network of Charging Stations (setting up of adequate public charging infrastructure) c) Administration of Scheme including Publicity, IEC (Information, Education & Communication) activities.
Maldives (45)	No EV policy yet	Global Environment Facility announced plans to help Maldives accelerate their shift to zero-emissions electric mobility (in its initial phase)
Nepal (46)	Environment friendly Vehicle and Transport Policy	Increase the share of EVs to 20% by 2020 and proposed subsidy schemes. But the market of the EVs dropped following the increase in 120%-140% of tax of combined excise and customs duties in the 2020-21 budget plan.

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Country	E-mobility policy	Targets/ Incentives
Pakistan (47)	National Electric Vehicles Policy (2020)	Passenger EV sales to constitute 30% of new sales by 2030 and 90% of new sales by 2040; 2 & 3 wheelers EV sales to constitute 50% of new sales by 2030 and 90% of new sales by 2040; Buses EV sales to constitute 50% of new sales by 2030 and 90% of new sales by 2040; and Trucks EV sales to constitute 30% of new sales by 2030 and 90% of new sales by 2040 Incentives includes: 1% GST for EVs (down from 17%), 1% Import Duty on charging equipment, Lower electricity tariffs for EV charging stations, State Bank to offer lower rate financing to EV manufacturers
Sri Lanka (48)		Global Environment Facility announced plans to help Sri Lanka accelerate their shift to zero-emissions electric mobility (in November 2021)

Source: Compiled by the authors

The continued growth of E-mobility for land transport will require investments in electric charging and related grid infrastructure, which has a direct relevance in terms of SDG 7 and clean power generation capacity. To ensure fast EV uptake for climate benefit through market mechanism, three barriers must be overcome in the next 10 years: battery costs, availability of charging infrastructure, and clean power generation and distribution (49). Dedicated high power charging stations can reduce charging time (50). These have been installed in several countries that have a relatively large market for EVs, such as China, UK, US, and Germany.

While market mechanism is vital to advance electric mobility, adequate policy support is an absolute necessity to enable the shift. In Sweden and Germany, for instance, electric heavy-duty vehicles are incentivised by electrified traffic lanes (51). The larger penetration of EVs requires innovative business models like MaaS (mobility-as-a-service), but studies have shown concern that MaaS may not work in low density car-dependent cities as the distances to be travelled are too long, which may not enable easy sharing that can happen in dense places (52).

Challenges

The increased emphasis on E-mobility through battery-operated vehicles is creating geopolitical issues in the energy sector and needs attention within the context of SDG 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) and 7.b (by 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States and landlocked developing countries, in accordance with their respective programmes of support). Countries like India are becoming importers of lithium batteries (used in EVs) in huge quantities given the lack of lithium, cobalt, and nickel reserves. In

Table 4: Regulatory Frameworks for Lithium-ion Battery Management

Regions	Framework	Treatment of Lithium-ion Batteries
EU	Battery Directive (2006)	Minimizing the negative impact of waste batteries, including lithium-ion batteries. Prohibition of disposal of industrial/ automotive batteries/accumulators to landfill or incineration Allowing the recycling and treatment of battery waste outside the EU if EU legislation for transport/transfer of hazardous waste are followed
US	Considered hazardous and are regulated under the Standards for Universal Waste Management (Electronic Code of Federal Regulations, Title 40, Part 273, US EPA).	The order strictly prohibits the disposal of batteries to landfills. However, the Federal Government standards do not include any directive about resource recovery from lithium-ion batteries waste. Some states in the USA are developing their own regulations that enforce producers to offer or fund battery recycling. These schemes are active in California, Minnesota, Iowa New York, Florida, Vermont, New Jersey, and Maryland.
China	Draft rules in 2017	Hold car manufacturers responsible for the recovery of new energy vehicle batteries and require them to set up recycling channels and service outlets where old batteries can be collected, stored and transferred to specialist recyclers.

Regions	Framework	Treatment of Lithium-ion Batteries
Japan	Law for the Promotion of the Effective Utilisation of Resources, 2000	Mandates that rechargeable batteries be classified for recycling, at the manufacturing stage, using a standardised three arrow recycling mark indicating battery type and primary metal components. On reaching end-of-life, these marked batteries are collected and recycled appropriately. The Law also sets lithium-ion batteries recycling target of greater than 30% and stipulates that all manufacturers and importers of batteries must have a recovery system for waste products
India	Draft rule- Battery Waste Management Rules, 2020	Explains in detail the responsibility of the battery manufacturer- from setting up battery-waste collection centres and take-back systems to affixing targets for battery-waste collection from two to seven years after the rules come into effect

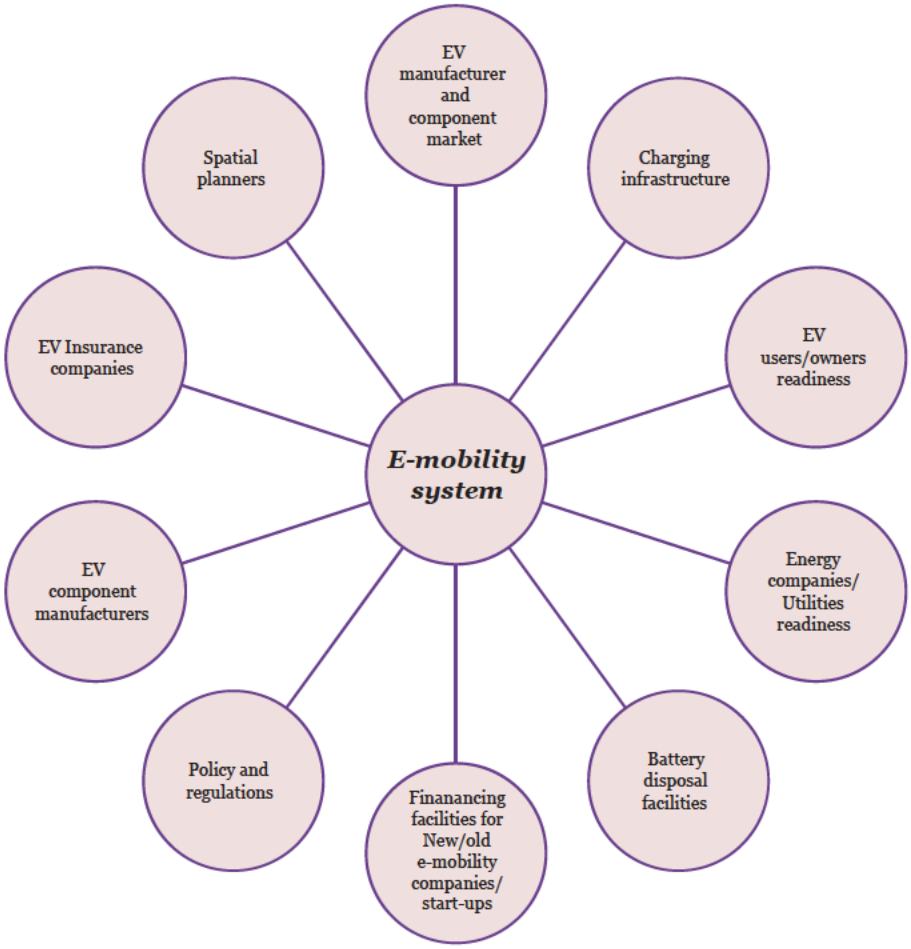
Source: Adapted from JMK Research & Analytics (57)

2019-20, India imported 450 million units of lithium batteries valued at INR 6,600 crore (US$929.26 million) (53).

EV batteries typically lifecycle of about eight years and need to be replaced when capacity falls below 80 percent (54). This can be done in two ways—EV batteries can be repurposed for secondary applications or can be sent for recycling and for metal to be recovered from them.

Spent batteries contain toxic materials, and proper waste management is vital to avoid fires and soil and water contamination. Studies suggest that recycling and repurposing lithium-ion batteries can create a circular economy and reduce the dependence on resources and materials used to make these batteries (55). Multiple countries are establishing regulatory frameworks to manage lithium-ion batteries (see Table 4). India's draft Battery Waste Management Rules, 2020 outlines the responsibility of

Figure 2: Actor Network for E-Mobility



Source: Prepared by the authors

the battery manufacturer, ranging from setting up battery-waste collection centres and take-back systems to affixing targets for battery-waste collection. Recycling or reusing lithium-ion batteries for stationary energy applications is another potential way to manged end-of-life batteries. However, access to information on the health of lithium-ion batteries remains a challenge for recycling and remanufacturing batteries for a second life (56).

In India's intermediate means of transport (IMT) segment, which is dominated by hydrocarbons, the penetration rate of E-rickshaws is much lower than the potential. This is due to conflicts (social, political and legislative) with the hydrocarbon

regime along with varying cultural bias for rickshaws despite the fast technology development in this segment. E-rickshaw technology is readily available but policy inertia, institutional preparedness, competition with the incumbent technology based on hydrocarbons are causing delays in transforming the IMT segment (58).

Importantly, a deep electrification in the transport sector may have an adverse impact on SDG 7 because increases in electricity demand can lead to an increase in prices, adversely affecting the affordability of modern energy for poor populations, unless pro-poor redistributive policies are in place (59). Decarbonising the transport sector will require significant integrated planning of transport and power infrastructure and the involvement of multiple social actors (see Figure 2) for systemwide benefits.

Conclusion

Considering E-mobility in the context of the climate goal (SDG 13) will likely conflict with the aims of SDG 7 (ensuring access to affordable, reliable, sustainable, and modern energy for all). Mobility-poor social groups can be categorised under active mobility service users and hence have a minimal impact on the environment. Social inequity in modern energy and mobility is connected to levels of wealth, poverty and capability. Viewing the Global South and North not as geographic regions but as 'social designations' for vulnerable communities provides a useful analytical framing—the Global South community has active mobility users with a minimum direct contribution to the environment but has less access to modern energy to meet the wellbeing needs. Global South as a social group that is living with low purchasing power, energy poverty and mobility deficit and is mostly dependent on active mobility, have the rights to enhance mobility and access to modern energy. At the same time, the automobility needs of the Global North have increased manifold in recent decades.

Mobility per se is not a problem, and can be better for health outcomes and overall human wellbeing (SDG 3) if it is in active mode. The overall demand for mobility can lead to an increase in energy use and emissions, unless managed properly. E-mobility is one solution.

Policymaking must keep abreast with this shift and to transform mobility practices. The growth in active mobility and its ability to replace automobility should be quantified to get an idea of avoidable and unavoidable mobility. Research must focus on the various social groups and particularly on the transition for the Global North. A systemic approach is needed to transition from fossil fuel-mobility to E-mobility in the Decade of Action.

Endnotes

(1) International Energy Agency,*Tracking Transport 2020*,Paris, IEA, 2020, https://www.iea.org/reports/tracking-transport-2020.

(2) UN Sustainable Development Goals, "Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development", https://unstats.un.org/sdgs/indicators/indicators-list/

(3) Joyashree Roy et al., "Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search," *Environmental Research Letters*, 2021, https://iopscience.iop.org/article/10.1088/1748-9326/abd81a/pdf

(4) "Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search"

(5) Jens Malmodin and Dag Lundén, "The energy and carbon footprint of the global ICT and E & M sectors 2010- 2015" *Sustain*., (2018). doi:10.3390/su10093027; G. Cook, G. et al., "Clicking clean: Who is winning the race to build a green internet?" *Greenpeace Inc*., (2017)

(6) Madhubani Ghosh and Joyashree Roy, "Climate action and maritime business education: the pedagogy of experiential learning," *IIRE Journal of Maritime Research & Development 3*, No. 2 (2019).

(7) Bronwyn Hayward and Joyashree Roy, "Sustainable living: bridging the north-south divide in lifestyles and consumption debates," *Annual Review of Environment and Resources*, No. 44 (2018).

(8) J. Roy and Foreman, "Ecomodern Justice", *Breakthrough Dialogue 2021*, (2021). https://thebreakthrough.org/journal/no-14-summer-2021/ecomodern-justice-summer-issue-intro

(9) Charlie Dannreuther and Rohit Lekhi, "Globalization and the political economy of risk," A Review of *International Political Economy 7,* no. 4 (2002).

(10) Bernhard Gunter and Rolph Van der Hoeven, "The social dimension of globalization," A review of the *Literature." Int'l Lab. Rev 143*, (2004).

(11) James Faulconbridge and Jonathan Beaverstock, "Globalization: Interconnected Worlds" in *Key Concepts of Geography*, ed. Sarah Holloway (London: Sage, 2008), 331-343.

(12) David Naguib-Pellow, *Resisting Global Toxics: Transnational Movements for Environmental Justice* (Cambridge, MA: MIT Press, 2007); Lucy Bell, "Place, people and processes in waste theory: a global South critique" *Cultural Studies 33,* No. 1(2019), 98-121; Hayward and Roy, "Sustainable living: bridging the north-south divide in lifestyles and consumption debates"

(13) Pengjun Zhao and Z Yu, "Rural poverty and mobility in China: A national-level survey,"

Journal of Transport Geography 93, No. 103083 (2021).

(14) Felix Creutzig et al., "Towards demand-side solutions for mitigating climate change," *Nature Climate Change 8,* No. 4 (2018), 260-263; Oswald, Y., A. et al., "Large inequality in international and intranational energy footprints between income groups and across consumption categories". *Nat. Energy*, No. 5 (2020), 231– 239,

(15) Joyashree Roy et al., "Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search"; B. Ghosh, "Transformation beyond experimentation: sustainability transitions in megacities" (PhD diss., University of Sussex, 2019), pp 99-120

(16) S. Liyanage et al., "Flexible mobility on-demand: An environmental scan," *Sustainability 11*, No.5 (2019).

(17) Felix Creutzig et al., "A typology of 100,000 publications on demand, services and social aspects of climate change mitigation," *Environmental Research Letters 16,* No. 3 (2021).; Creutzig et al., "Towards demand-side solutions for mitigating climate change," *Environmental Research Letters 16,* No. 3 (2021); Roy et al., "Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search," *Environmental Research Letters 16,* No.4 (2021), pp 32.

(18) Joyashree Roy et al., "Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search," *Environmental Research Letters 16,* No.4 (2021), pp 32.

(19) Sohani Liyanage et al., "Flexible mobility on-demand: An environmental scan," *Sustainability 11*, No. 5 (2019), 1262.

(20) Bipashyee Ghosh, "Transformation beyond experimentation: sustainability transitions in megacities" (PhD diss., University of Sussex, 2019), pp 99-120 "Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search," *Environmental Research Letters 16,* No.4 (2021), pp 32.

(21) Joyashree Roy et al., "Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search," *Environmental Research Letters 16,* No.4 (2021), pp 3; Liyanage et al., "Flexible mobility on-demand: An environmental scan,"*Sustainability 11*, no. 5 (2019), 1262

(22) UNESCO, *Report of the Inter-agency and Expert Group on Sustainable Development Goal Indicators*, New York, United Nations (2017), pp 49. http://unstats.un.org/sdgs/iaeg-sdgs/; UNFCCC, *Sustainable Development Goals Knowledge Platform*, New York, UNFCC (2015), https://sustainabledevelopment.un.org/?menu=1300

(23) Christian Brand et al., "The climate change mitigation effects of daily active travel in cities," *Transportation Research Part D: Transport and Environment 93*, (2021).

(24) Priyadarshi Shukla et al., "Electric Vehicles Scenarios and a Roadmap for India", *UNEP DTU Partnership* (2014).

https://backend.orbit.dtu.dk/ws/portalfiles/portal/104752085/Electric_Vehicle_Scenarios_and_a_R oadmap_for_India_upload.pdf; Roy et al., "Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search," *Environmental Research Letters 16,* No.4 (2021).

(25) Erol Gelenbe and Yves Caseau, "The impact of information technology on energy consumption and carbon emissions," *Ubiquity*, (2015), 1-15; G. Cook, G. et al., *Clicking clean: Who is winning the race to build a green internet?*, Amsterdam, Greenpeace Group, 2020, https://www.actu-environnement.com/media/pdf/news-28245-clicking-clean-2017.pdf

(26) World Bank, "World Development Indicators, Railways, passengers carried (million passenger-km) – World (2021a)", https://data.worldbank.org/indicator/IS.RRS.PASG.KM?locations=IN-1W; World Bank, "World Development Indicators, Railways, goods transported (million ton-km) – World (2021b)", https://data.worldbank.org/indicator/IS.RRS.GOOD.MT.K6?locations=1W; World Bank, "World Development Indicators, Air transport, freight (million ton-km) – World (2021c)", https://data.worldbank.org/indicator/IS.AIR.GOOD.MT.K1?locations=1W; World Bank, "World Development Indicators, Air transport, passengers carried – World (2021d)", https://data.worldbank.org/indicator/IS.AIR.PSGR?locations=1W; Global Energy Assessment, "Global Energy Assessment - Toward a Sustainable Future," Cambridge University Press and International Institute for Applied Systems Analysis, 2012, https://previous.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Home-GEA.en.html

(27) "The global electric bike market is projected to grow from $18.58 billion in 2021 to $52.36 billion in 2028 at a CAGR of 16.0% in forecast period, 2021-2028," *Fortune Business Insights*, https://www.fortunebusinessinsights.com/electric-e-bike-market-102022

(28) "India Electric Rickshaw (E-Rickshaw) Market: Insights and Forecast up to 2030," *Benzinga*, November 29, 2021, https://www.benzinga.com/pressreleases/21/11/24326622/india-electric-rickshaw-e-rickshaw-market-insights-and-forecast-up-to-2030

(29) "These countries have the most electric cars; check list," *Livemint*, August 12, 2021, https://www.livemint.com/auto-news/global-evs-sale-climbs-up-here-s-list-of-countries-with-most-electric-cars-11628745051665.html

(30) Department of Heavy Industry, Ministry of Heavy Industries & Public Enterprises, Government of India, "Operational guidelines for Delivery of Demand Incentive Under FAME India Scheme", December 2019, https://www.dhi.nic.in/writereaddata/fame/famedepository/19-E__didm_WriteReadData_userfiles_guideline.pdf; "India Electric Rickshaw (E-Rickshaw) Market"

(31) "Electric Truck Market Size, Share & Trends Analysis Report By Vehicle Type (Battery Electric Trucks, Hybrid Trucks), By Region, And Segment Forecasts, 2020 – 202," Grand View Research, September 2020, https://www.grandviewresearch.com/

industry-analysis/electric-trucks-market

(32) "Get to your destination with renewable power," Deutschebahn, https://gruen.deutschebahn.com/en/measures/ice

(33) Mordor Intelligence Industry Reports, "Electric boat and ship market - growth, trends, covid-19 impact, and forecast (2022 - 2027)," Mordor Intelligence, https://www.mordorintelligence.com/industry-reports/electric-boat-and-shipmarket

(34) Sumit Banerjee, "Kolkata was the first city in Asia to get the electric tram!," *Get Bengal*, March 4, 2020, https://www.getbengal.com/details/kolkata-was-the-first-city-in-asia-to-get-the-electric-tram (35) Niklas Höhne et at., "A seismograph for measuring the transformation to net zero greenhouse gas emissions–discussion paper," *New Climate Institute,* (2021). https://datadrivenlab.org/wpcontent/uploads/2021/11/DiscussionPaper_Transformation-seismograph_Nov21.pdf

(36) "Operational guidelines for Delivery of Demand Incentive Under FAME India Scheme"

(37) Sohail Ahmad and Felix Creutzig, "Spatially contextualized analysis of energy use for commuting in India," *Environmental Research Letters 14*, No. 4 (2019), doi:10.1088/1748-9326/ab011f.

(38) Christopher R. Cherry et al., "Dynamics of electric bike ownership and use in Kunming, China," *Transport Policy 45,* (2016), 127-135

(39) Joyashree Roy et al., *Critical Junctions on the Journey to 1.5°C: The Decisive Decade,* London/The Hague, Climate Strategies, 2021

(40) Girard Aymeric & Simon François, "Case study for Chile: The electric vehicle penetration in Chile," *Electric Vehicles: Prospects and Challenges,* (2017), 245-285.

(41) Adam Vanzella et al., "Move: test case for electric carsharing at Itaipu" (paper presented at 21st International Conference on Intelligent Transportation System, 2018).

(42) Ashraf Hossain Bhuiyan, "Electric-mobility in Bangladesh prospects and possibilities," *Financial Express*, October 8, 2021, https://thefinancialexpress.com.bd/views/electric-mobility-in-bangladesh-prospects-and-possibilities-1633702313

(43) Lhaba Tshering, "Bhutan Electric Vehicle Initiative" (paper presented at the BAQ Conference, Colombo, Sri Lanka, November 2014) https://www.uncrd.or.jp/content/documents/22548EST-P2_Bhutan.pdf

(44) Government of India, Faster adoption and manufacturing of hybrid and electric vehicles Phase II (FAME II)

(45) UN Environment Programe, "UN-led partnership to accelerate electric mobility shift in 27 countries," UNEP, November 10, 2021, https://www.unep.org/news-and-stories/press-release/un-led-partnership-accelerate-electric-mobility-shift-27-countries

(46) "This is how Nepal should improve its electric vehicle policies" *OnlineKhabar*, 2021,

https://english.onlinekhabar.com/electric-vehicle-policies-nepal.html

(47) Moaz Uddin, comment on "Pakistan's national electric vehicle policy", *The International Council on Clean Transportation*, January 10, 2020, https://theicct.org/pakistans-national-electric-vehicle-policy-charging-towards-the-future/

(48) UNEP, "UN-led partnership to accelerate electric mobility shift in 27 countries"

(49) "Critical Junctions on the Journey to 1.5°C: The Decisive Decade"

(50) Priyadarshi Shukla et al., "Electric Vehicles Scenarios and a Roadmap for India"

(51) "Critical Junctions on the Journey to 1.5°C: The Decisive Decade"

(52) Peraphan Jittrapirom et al., "Mobility as a service: A critical review of definitions, assessments of schemes, and key challenges." Urban Planning (2017). https://www.cogitatiopress.com/urbanplanning/article/view/931

(53) Ministry of Science and Technology, Government of India, Lok Sabha UNSTARRED QUESTION No.1018, http://164.100.24.220/loksabhaquestions/annex/173/AU1018.pdf

(54) Nikhil Ghanekar, "India faces two major challenges in its transition to electric vehicles,." *Scroll*, April 25, 2021, https://scroll.in/article/992703/india-faces-two-major-challenges-in-its-transition-to-electric-vehicles

(55) JMK Research & Analytics, "Recycling of lithium-ion batteries in India- $1,000 million opportunity." (2019). https://jmkresearch.com/electric-vehicles-published-reports/recycling-of-lithium-ion-batteries-in-india1000-million-opportunity/; Lohani, "Recycling Li-ion batteries: Opportunities and challenges." (2020). https://www.orfonline.org/expert-speak/recycling-liion-batteries-opportunities-challenges-68409/

(56) Leil Ahmadi et al., "A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems," *The International Journal of Life Cycle Assessment 22*, No. 1 (2017), 111-124.

(57) JMK Research & Analytics, "Recycling of lithium-ion batteries in India- $1,000 million opportunity."

(58) Joyashree Roy et al., "Where is the hope? Blending modern urban lifestyle with cultural practices in India," *Current Opinion in Environmental Sustainability 31,* (2018), 96-103.
(59) Carmen Klausbruckner et al., "A policy review of synergies and trade-offs in South African climate change mitigation and air pollution control strategies," *Environmental Science & Policy 57*, (2016), 70-7



Model complementarity exercise on demand-side innovations for climate change mitigation

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Summary

Last year, we made a call for data submission within the EDITS community and did a rudimentary scenario data comparison between models including RECC, DNE21+, MESSAGE-Buildings and COFFEE. During that exercise, we found that the actual low-demand scenarios vary widely among the models. To enhance the validity of model comparison, this year we launched the model complementarity exercise (MCE) during the annual meeting. In the protocol for the MCE, we clarified the goals and workflow of MCE to all modeling teams in EDITS community. At the same time, we released the list of input variables derived from DETRAS model to make sure all participating models follow the same scenario narrative and quantification guidelines. Besides, a list of output referring to IAMC data template were provided to collect data from models. Collaborating with IIASA researchers, we gradually set up the platform, IIASA EDITS Scenario Explorer, for the sake of data submission and comparison. Next year, the activity level, structure, intensity, and final energy among all models will be comprehensively analyzed and compared to better understand the model similarities and differences toward demand-side solutions.

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

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Global and regional opportunities and constraints posed by the industrial sector on the path to 1.5 degrees under the aegis on an integrated assessment model

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Global and regional opportunities and constraints posed by the industrial sector on the path to 1.5 degrees under the aegis on an integrated assessment model

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Global and regional opportunities and constraints posed by the industrial sector on the path to 1.5 degrees under the aegis on an integrated assessment model

ABSTRACT

The dependence on fossil fuels has been a central feature of industrial activity since the Industrial Revolution. And in the 20th century, oil abundance represented a shift not only in the provision of energy but also of materials services. Materials such as plastics, fibers and fertilizers radically changed how modern society produces and consumes products and have given the petrochemical industry a significant importance due to its non-energy use of fossil fuels, which are generally overlooked by mitigation efforts in IAMs.

The petrochemical industry is responsible for around 14% and 8% of the global oil and gas consumption, respectively. Global plastics production capacity has increased by 4% per year since 2000, whereas only one fifth of all plastics ever produced has been recycled or incinerated. If this trend continues or increases by the use of petrochemicals in new energy converters (e.g., wind turbine blades and solar panels), CO2 emissions related to plastics production can be expected to increase by 40% by 2030 and mismanaged plastics waste could triple by 2060.

The aim of this work is to explore the Industrial Sector and improve the understanding of the dynamics of change in oil use for non-energy purposes in climate stringent scenarios from a global integrated assessment model (IAM) perspective. Long-term fuel use, technological portfolios and CO2 emissions for petrochemicals production are regional and globally evaluated with the use of the COFFEE model, a process-based technology-rich global optimization IAM based on the MESSAGE platform. To analyze the future role of carbon-based feedstocks, five scenarios are developed combining different future demand, final disposal, and carbon pricing assumptions.

Results show that future chemical demand may extend the lifetime of oil refineries in certain regions even in carbon stringent scenarios. However, the development of bio-refineries could play an important role in supplying bio-naphtha in synergy with the provision of low-carbon fuels for hard-to-abate sectors, such as aviation and shipping. The reduction of packaging demand together with the increase of mechanical recycling relieve the pressure to reduce emissions from the chemical sector in carbon stringent scenarios, but only to a certain limit. These transformations will be key for the development of the Industrial Sector of the future.

1. INTRODUCTION

Fossil fuels play a key role in the petrochemical industry as being the main sources to manufacture goods such as plastics, synthetic fibers, and fertilizers that provides essential services for our society Yet, currently, integrated assessment models (IAMs) have very limited representation of the non-energy and chemicals sectors, thus overlooking potential environmental benefits brought about by promoting circular economy and the use of alternative feedstocks such as biomass and CCU.

This assessment holds significant importance for multiple reasons. The petrochemical industry is responsible for around 14% and 8% of the global oil and gas consumption, respectively [1]. Plastics production, which responds for around half of the petrochemical industry's CO_2 emissions, has considerable environmental impacts [2]. Plastic products are frequently disposed of improperly, and they can persist in the environment for hundreds of years, causing significant harm to ecosystems, polluting the oceans, and resulting in various other environmental problems [3]–[6].
An aggravating factor is that global plastics production capacity has increased by 4% per year since 2000, whereas only one fifth of all plastics ever produced has been recycled or incinerated [7]. If this trend continues or increases using petrochemicals in new energy converters (e.g., wind turbine blades and solar panels), CO_2 emissions related to plastics production can be expected to increase by 40% by 2030 and mismanaged plastics waste could triple by 2060 [8]. An aggravating factor is that global plastics production capacity has increased by 4% per year since 2000, whereas only one fifth of all plastics ever produced has been recycled or incinerated [7]. If this trend continues or increases using petrochemicals in new energy converters (e.g., wind turbine blades and solar panels), CO_2 emissions related to plastics production can be expected to increase by 40% by 2030 and mismanaged plastics waste could triple by 2060[8]. In recent years, the petrochemical industry has come under increased scrutiny for its impact on the environment and climate change. Efforts are being made to reduce the industry's carbon footprint, such as improving energy efficiency, increasing the use of renewable energy sources, and developing new technologies for capturing and storing carbon dioxide.
IAMs therefore will need to be capable of assessing the impact on mitigation scenarios of these alternative abatement measures such as retaining carbon in materials through circular economy measures, preventing them from being released into the atmosphere at the end of their useful life. Furthermore, modeling possibilities for negative carbon stocks using substitute feedstocks such as biomass in manufacturing products [9]–[11].

Thus far, a few significant IAMs have observed the benefits of circular economy and bioproducts in the petrochemical sector. One of the first models that tried to investigate decarbonization opportunities for non-energy uses of fossil feedstock was the global Non-Energy Demand and Emissions simulation model (NEDE), which was incorporated into the Integrated Model to Assess the Global Environment (IMAGE) model to evaluate the role of biomass for non-energy use in reducing carbon emissions [12]. Although recycling and incineration have been considered, a more recent model development named plastics integrated assessment model (PLAIA) has allowed the evaluation of these measures in greater detail across different life cycle stages[13], [14]. The PLAIA model has integrated a dynamic plastics stock and flow model that allows for a more accurate assessment of plastics availability for post consumption processes such as recycling and incineration. Other new features are the possibility of new routes using CO_2 for methanol production, which allows biogenic carbon sequestration in plastic products and chemical recycling options via pyrolysis [14].

Meys et. Al (2021) also studied alternatives for the sector to achieve net-zero emissions by using a bottom-up model for the petrochemical sector capable of considering the entire life cycle of about 90%

of all polymer types marketed worldwide [15]. The authors evaluated the possibility of circular carbon pathways in which recycling, biomass feedstock utilization and Carbon Capture and Utilization (CCU) options are applied together to reduce the residual carbon emissions that usually occur when these mitigation options are applied alone. In this way they managed to achieve a reduction of final energy demand and carbon emissions became slightly negative[15]. In this same direction, Sun et al. 2022, also concluded that bioplastic can be a potential carbon reservoir [16].

Beyond this, other possibilities for reusing waste from other sectors have also been considered. In Sluisveld et. Al (2021) evaluated mitigation options for the petrochemical industry in IMAGE model by considering percentages of plastic waste reuse through recycling and black liquor use from the paper and pulp sector[17] .

Although these studies demonstrate the benefits of using circular economy measures and biomass in the petrochemical sector, there is a trade-off between recycling plastic waste, which reduces the need for primary raw materials but can also be an energy-intensive process, and the use of biomass, which can store biogenic carbon in long-life plastic materials [14], [15].

A major additional issue that requires careful evaluation is the possibility of biomass use competition for other purposes such as nutrition and energy production. In this respect, Oliveira et al. (2021) performed an original work evaluating the biomass trilemma[1] in the BLUES national integrated assessment model. By including biomass conversion routes into the petrochemical sector, the authors concluded that in climate constrained scenarios biomass has a key role both for carbon storage and to produce green biofuels. They also pointed to the importance of investments in biorefineries to alleviate the competition between food, energy, and materials, since in this case several co-products could be produced in the same plant [18].

Taken together, these studies support the continued need to further explore how circular economy measures can assist carbon mitigation in sectors that are currently heavily dependent on fossil fuels. And besides the fact that only a few IAMs are currently able to perform this evaluation, these models are distinct in their assumptions and technological structures and therefore, it is imperative that more models become capable of studying potential pathways towards decarbonization of the petrochemical sector.

Thus, this paper aims to contribute to the representation of materials in IAMs by developing a specific case study for the petrochemical sector in which the dynamics of change in oil use for non-energy purposes and the contribution and the limits of plastic demand reduction and recycling are evaluated.

For this purpose, the COFFEE IAM was used, in which the petrochemical sector was first upgraded to be able to evaluate alternative plastic production and post-consumer treatment routes. Next, several climate constrained scenarios were developed in which we investigated how the implementation of bioproducts, and the circular economy can help to achieve emissions targets.

As such, this study is organized as follows: Section 2 describes the integrated assessment model used in this research as well as the methods to develop the case study and exogenous assumptions, and Section 3 presents the main results. Finally, Section 4 provides contains the main conclusions of this work and provides a discussion and limitations of this research.

[1] Biomass trilemma is referred as the competition between energy, food, and materials use of biomass.

2. METHODS

In this section, we describe the methodology for assessing long term global energy use and CO_2 emissions from the chemicals sector based on plastics demand and final disposal scenarios. First, we present the COmputable Framework For Energy and the Environment model (COFFEE), a global IAM used to address the research questions, and the model improvements carried out to explicitly represent the chemical sector within the framework. Then, we describe the method used to create plastics demand and final disposal scenarios, and how they were later implemented as exogenous inputs to COFFEE.

2.1. The COFFEE model

COFFEE is a perfect foresight, linear programming, least-cost optimization model [19]. It is based on the MESSAGE platform, developed by the International Institute for Applied System Analysis (IIASA) [20], [21], which evaluates the energy, building (residential and commercial), passenger and freight transport, industrial, and waste and residue sectors, as well as land-use changes. Created in COPPE/UFRJ, COFFEE depicts in 18 regions the completely integrated global energy and land-use systems and is designed to support policymaking by evaluating potential trade-offs and synergies between climate, environmental and energy systems. The model uses linear programming for intertemporal optimization, and it aims to minimize the cost of the entire energy system and land use, while meeting the demand for energy and food services, subject to restrictions. Its time horizon extends until 2100 divided into fourteen-time steps. Detailed information on the COFFEE model structure is found in the Supplementary Material (SM).

2.2. Technology representation of the chemical industry

The representation of the chemical sector in COFFEE is divided in three modules – *Bulk Organic Chemicals*, *Non-energy* and *Other Chemicals*. The *Bulk Organic Chemicals* module includes detailed and explicit representation of both conventional and innovative technologies that produce key organic bulk materials - ethylene, propylene, butadiene, BTX (aromatics), ammonia[2] and methanol. The *Non-energy* module supplies hydrocarbon-based feedstocks to the organic chemical module and to the production of other non-energy refinery products (e.g., lubricants, bitumen). The *Other Chemicals* module corresponds to the heat, steam, and electricity consumption to produce the remainder of the chemicals (e.g., chlor-alkali, potash), based on the data from the *World Energy Balances* [1].

The reasoning for the scope of the *Bulk Organic Chemicals* module has two key aims. First, to represent important aspects of the chemicals industry structure today, including the multi-product nature of the steam cracking process, the co-production of propylene and aromatics in oil refineries, the expansion of propylene on-purpose routes due to recent increase in global capacity of ethane steam crackers, and the increasingly relevant coal-based chemicals capacity in China. Second, we aimed at allowing the model to supply each of the products with fossil fuels, biomass, or CCU-based feedstocks (see Figure 1). For instance, butadiene can be produced either in conventional naphtha steam cracking (fossil), by converting bioethanol (bio), or by hydrogenation of CO_2 in methanol, which is then converted to ethylene via Methanol-to-Olefins, and then to butadiene via dimerization followed by the Catadiene process.

Figure 1 depicts the technology-rich module represented within the COFFEE framework and *Table 1Table 2* contain the technoeconomic assumptions of traditional and innovative technologies to

[2] Though ammonia is rigorously an inorganic compound, it is usually produced by the reaction of natural gas-based H_2 and N_2. Thus, we allocated it in organic bulk chemicals' module.

produce HVCs and methanol. Further detail can be found in the Supplementary Material (SM), where we describe each technology and categorize then either as *Multiproduct*, *On-purpose* or *Refinery co-production* routes. The scope of this study is limited to HVCs, ammonia technologies and assumptions are not described in this paper although being explicitly represented of the chemical module.

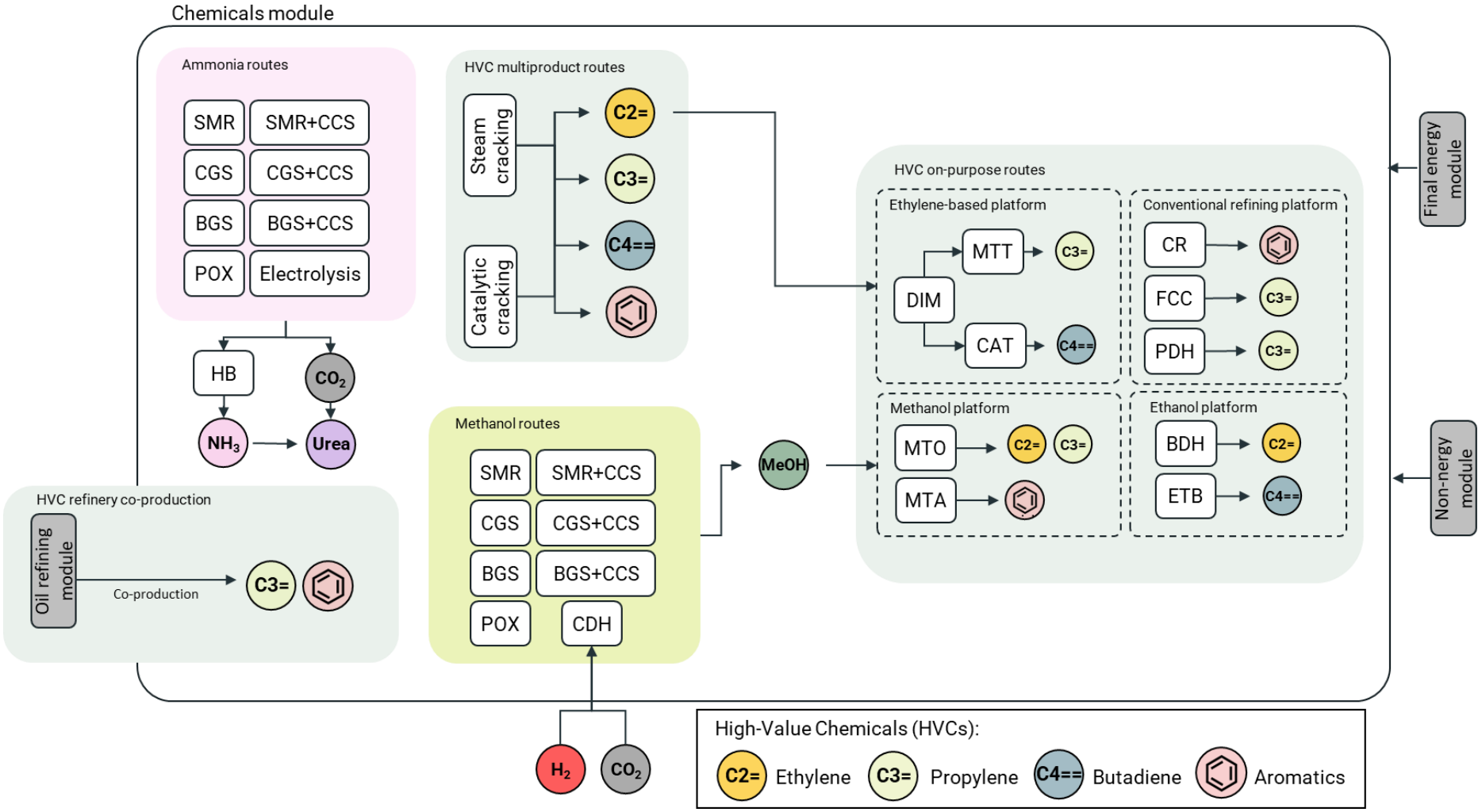


Figure 1. Bulk organic chemicals module

SMR: Steam Methane Reforming; CGS: Coal Gasification; BGS: Biomass Gasification; POX: Partial Oil Oxidation; HB: Haber Bosch synthesis; CDH: Carbon Dioxide Hydrogenation; DIM: Dimerization; CAT: Catadiene®; MTT: Metathesis; CR: Catalytic Reforming; FCC: Fluidized Catalytic Cracking; PDH: Propane Dehydrogenation; BDH: Bioethanol Dehydration; ETB: Ethanol to Butadiene; MTO: Methanol to Olefins; MTA: Methanol to Aromatic

Table 1 - Techno-economic parameters of HVC production technologies.

Technology	Feedstock	Output yields						SEC[a]	Plant capacity	Investment cost	O&M cost		Ref.
		Ethylene	Propylene	Butadiene	BTX	C4 stream	H_2				FOM	VOM	
		t/t_F						GJ/GJ_F	kt_{MO}/yr	USD2010/ $t_{MO}py$[b]	USD2010/t_{MO}		
SC-Naphtha	Naphtha	**0.324**	0.168	0.050	0.104			10	500	2718	54	54	[10], [22]–[25]
SC-Naphtha-b	Bionaphtha	***0.324***	*0.168*	*0.050*	*0.104*			10	500				
SC-NG	Ethane	**0.803**	0.016	0.023	0			15	500	1680	34	34	
NCC	Naphtha	**0.324**	0.324	0.050	0.130			9.3	400	3963	41	41	[10], [22], [26], [27]
NCC-b	Bionaphtha	***0.324***	*0.324*	*0.050*	*0.130*			9.3	400				
BDH	Ethanol	***0.575***						2.8	200	1190	84	84	
MTO	Methanol[c]	**0.190**	0.180					4.3	500	1340	34	34	[10], [22], [28]–[32]
MTO-b	Biomethanol	***0.190***	*0.180*					4.3	500				
PDH	Propane		**0.750**			0.19		9.1	500	855	23	23	[10], [22], [33], [34]
PDH-b	Biopropane		***0.750***			*0.19*		9.1	500				
MTT	Ethylene (+ C4s)[d]		**3.125**					3.6	300	750	44	44	[35], [36]
MTT-b	Bioethylene (+ bC4s) [d]		***3.125***					3.6	300				
ETB	Ethanol			***0.280***				21.5	50	800	67	23	[37]
MTA	Methanol[c]				**0.230**			3.8	500	1380	17	17	[10], [22], [28], [31]
MTA-b	Biomethanol				***0.230***			3.8	500				
CAT	C4 stream			**0.600**				11.4	500	855	23	23	[10], [22], [33], [34]
CAT-b	Bio C4 stream			***0.600***				11.4	500				
DIM	Ethylene					**0.800**		0.4	300	150	4	4	[35]
DIM-b	Bioethylene					***0.800***		0.4	300				
CR	Naphtha				**0.880**		3.6[e]	0.8	800	262	3	3	[38], [39]
CR	Bionaphtha				***0.880***		3.6[e]	0.8	800	262	3	3	[38], [39]

F: Feedstock (underlined); **MO: Main output (values in bold).** *Bioproducts in italic.* [a] Includes heat, steam, and machine drive requirements (thus excluding energy use as feedstock). [b] Tonnes per year. [c] [F]ossil-. or CCU-based. [d] Yields refer to 1t of ethylene and 3.03t of C4s. [e] Value in GJ/t_{MI}. SC: Steam cracking; NCC: Naphtha catalytic cracking; BDH: Bioethanol dehydration; MTO: Methanol-to-Olefins; PDH: Propane dehydrogenation; MTT: Metathesis; ETB: Ethanol-to-Butadiene; MTA: Methanol-to-Aromatics; CAT: Catadiene®; DIM: Dimerization; CR: Catalytic reforming; Suffix -*b*: bio-based feedstock and products.

Table 2 - Techno-economic parameters for methanol production technologies.

Technology	Feedstock	Yields		Machine drive requirement	Process Emissions	Investment cost	O&M cost		Ref.
		MO: Methanol	CO_2 *capture*/**use**				FOM	VOM	
		GJ_F [a] /t_{MO}	tCO_2/t_{MO}	GJ/t_{MO}	tCO_2/t_{MO}	USD2010/t_{MO}py [b]	USD2010/t_{MO}		
SMR	Methane	33.9	-	0.3	0.8	340	4.5	4.5	[40]–[42]
SMR+CCS	Methane	33.9	*0.76*	0.3	0.04	540	6.7	6.7	[40]–[42]
CGS	Coal	46.3	-	3.7	3.3	820	10.3	10.3	[40]–[42]
CGS+CCS	Coal	55.3	*3.14*	3.9	0.17	1020	12.8	12.8	[40]–[42]
BGS	Solid biomass	47.9	-	5.0	0	5655	70.7	70.7	[40]–[43]
BGS+CCS	Solid biomass	47.9	*3.25*	5.0	0	5855	73.3	73.3	[40]–[43]
CDH	H_2 + CO_2	22.6	**1.38**	1.5	0	44	0.5	0.5	[40]–[42], [44]

F: Feedstock (underlined); MO: Main Output; FOM: Fixed operation and maintenance cost; VOM: Variable operation and maintenance cost

2.3. High-value chemicals demand scenarios

Resin and fibres production are the main drivers of high-value chemicals (HVC) demand. Thus, to calculate the long term demands for each HVC, we started by using country-specific data of plastics consumption per capita in 63 countries as a proxy to calculate total plastic demands from 2010 to 2100 for the 18 regions in COFFEE [45]. Figure 2 depicts the historical data used in this study.

A regression analysis is then performed to calculate future demand projections, for which we used GDP and population data according to the second shared socioeconomic pathway (SSP2) [46]. We use a simple modified form of exponential growth model (Equation 1) based on macroeconomic assumptions to project long-term demands:

$$Cpc_t = Cpc_{t-1} \cdot \left(\frac{GDPpc_t}{GDPpc_{t-1}}\right)^{\frac{ln\left(\frac{Cpc_{2015}}{Cpc_{2010}}\right)}{ln\left(\frac{GDPpc_{2015}}{GDPpc_{2010}}\right)}} \quad (1)$$

Where Cpc_t is plastics consumption per capita in year t, and $GDPpc_t$ is the gross domestic product per capita in the year t. The model uses the ratio of growth rates between the current year and the previous year to adjust the rate of growth changes over time. Additionally, the logarithmic term normalizes the projection based on historical trends by comparing the ratio of plastic consumption per capita in a base year (i.e., 2015) to a prior year (i.e., 2010) with the ratio of growth rates over the same period. Due to low availability data, we decided to undertake this conservative approach to estimate future consumption per capita (i.e., it assumes that plastic consumption will continue to grow at a rate proportional to its current level, and that the rate of growth will be constant over time).

We compared the first results with other studies and reached the conclusion that: 1) the primary data for plastics per capita consumption had a reduced scope compared to the assessment made by [7], [10], and 2) HVCs are also used in other applications such as solvents, surfactants and detergents. Thus, to account for this “other” component of HVC demand, we normalized global demands based in the figures provided by Geyer et al. (2017). We then calculated the content of ethylene, propylene, butadiene, and BTX in 1 kg of plastic, based on figures from a material flow analysis work of 2013 [47], [48]. These shares were assumed to remain constant over time.

Regional demands for ethylene, propylene, butadiene, and aromatics from 2010 (base year) to 2100 were used as inputs to COFFEE as the baseline demand. In Section 2.4, there will be a detailed description on the stock-flow dynamic model utilized to create additional demand scenarios.

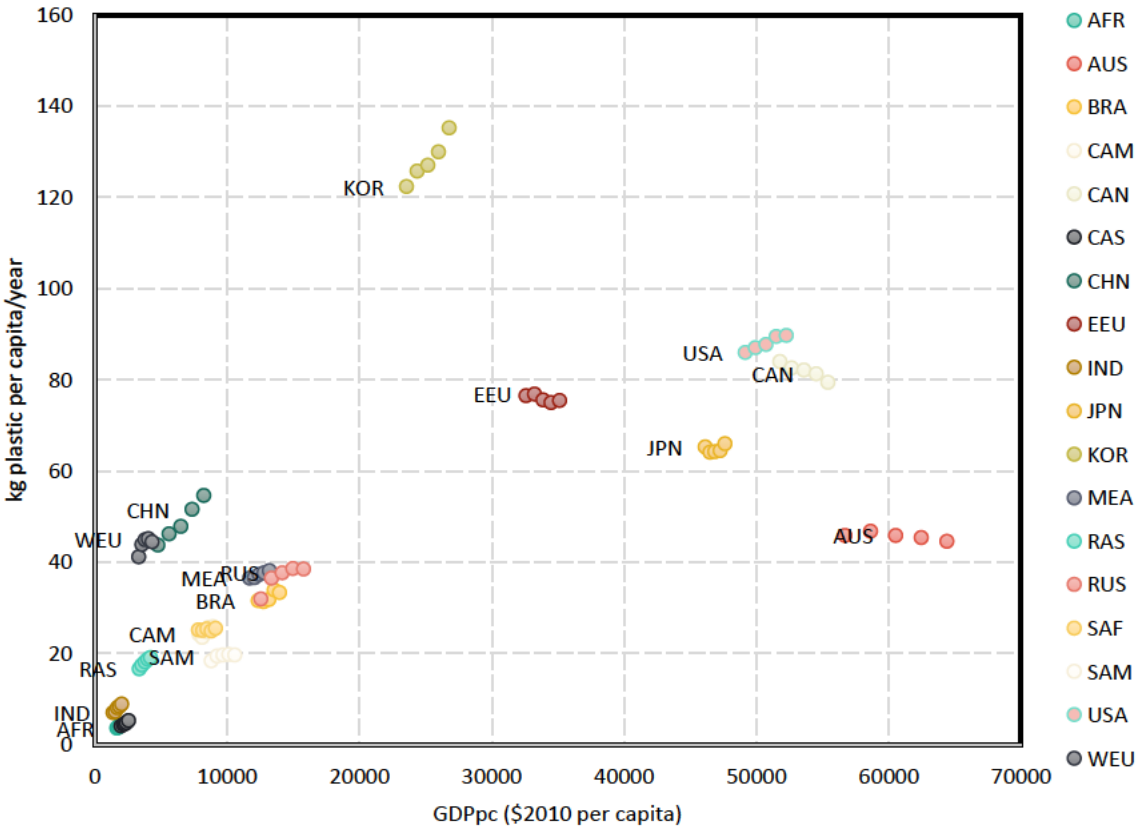


Figure 2. Development of per capita consumption of plastics per region.

To calculate methanol long term regional demands, a similar approach was followed. Given that methanol use in biodiesel production and gasoline blending was already endogenously represented in COFFEE, we model methanol demand for non-energy purposes separately, e.g., formaldehyde, acetic acid, and methylamine production. To that end, data on regional methanol demands were collected from EPE (2019) and Su et al. (2013)[49], [50], from which it was reduced the energy-related demands based on Chatterton (2018) and OECD & FAO (2021) [51], [52].

2.4. Plastics final disposal and waste scenarios

In this section we describe the methodology for the development of a global dynamic material flow analysis model for plastics to analyse potential effects of demand reduction in feedstock use and emissions, as well as in waste availability.

First, we matched the plastics demand calculated via regression analysis with country-specific data of: 1) type of plastics share (LLDE, HDPE, PP, PET, PVC, PUR, and others); and 2) industrial use of each type of plastic per sector (Packaging, Buildings/Construction, Electric/Electronic, Automotive, and others). Whenever this info was not available, the shares of plastic production according to polymer type and industrial use sector was given by Geyer et al. (2017).

Then, we developed a simplified dynamic stock-flow model to estimate when and where plastic waste would be generated based on lifetime distribution of each application, given by Geyer et al. (2017) (see *Figure 3*).

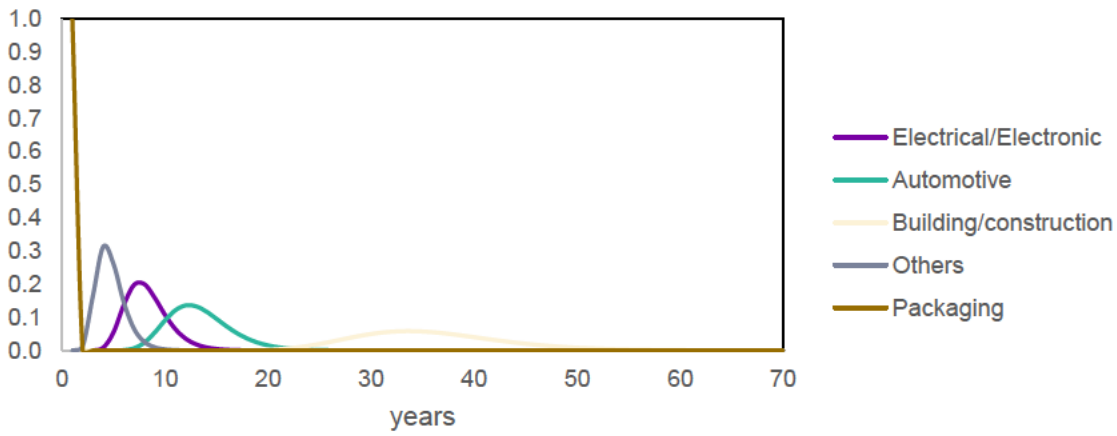


Figure 3. Lifetime distributions per sector. Source: [7].

We used this methodology to calculate the emissions resulting from final disposal and the amount of plastic waste generated in each region/time period. This information is critical to understand how policies aiming at reducing short-lived plastic consumption and at increasing recycling rates interrelate. Solid waste management data from World Bank's *What a Waste 2.0* databased was used as a baseline to estimate regional shares for incineration, landfilling (i.e., controlled landfilling plus mismanagement) and recycling [53] (see Figure 4).

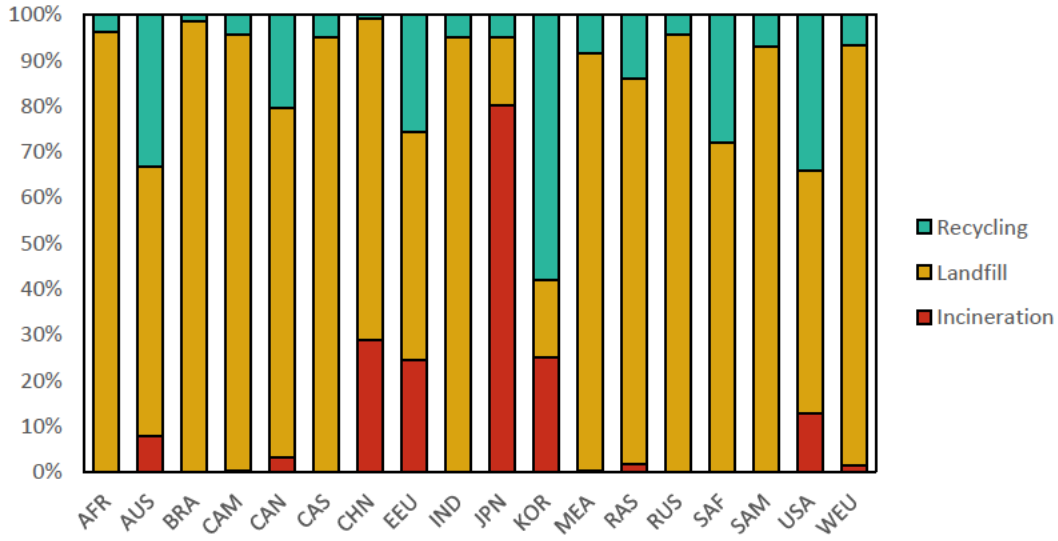


Figure 4. Final disposal shares assumed in the base year for COFFEE regions. Source: adapted from [53] .

Final disposal emissions were then endogenously calculated in COFFEE based on the final disposal scenarios, which in turn were given by the regional waste availability in each timestep. The assumptions underlying each final disposal scenario will be further described in the following subsection. It is important to mention that material demands are not linked to services demand, nor to products demand (e.g. plastic bottles). Plastic inflows are given by a historical trend driven by macroeconomic variables, thus not directly related to a specific human need or societal function, as opposed to energy services represented in COFFEE (e.g., illumination, thermal comfort, transport). Although currently there are many efforts in this direction (i.e., add not only flow-based but also stock-based service provision), this is a limitation of most IAMs, which have roots in efforts that aim to analyze energy-related effects on the climate system.

2.5. Scenario Development

This subsection describes the rationale behind the scenario development for plastic demand, final disposal, and carbon pricing to understand global effects in CO_2 emissions and energy use. The scenarios considered in this work were underpinned by the fact that key variables such as the demand for plastics, the waste availability for post-consumer processing, and potential carbon constraints directly influence the choice of technological routes and circular economy options.

As such, the three main subsets of interrelated scenarios are shown in Figure 5 and described below. The time horizon of analysis for all scenarios is from 2020 to 2060. The synthesis of assumptions taken for each scenario are also presented in *Table 3*.

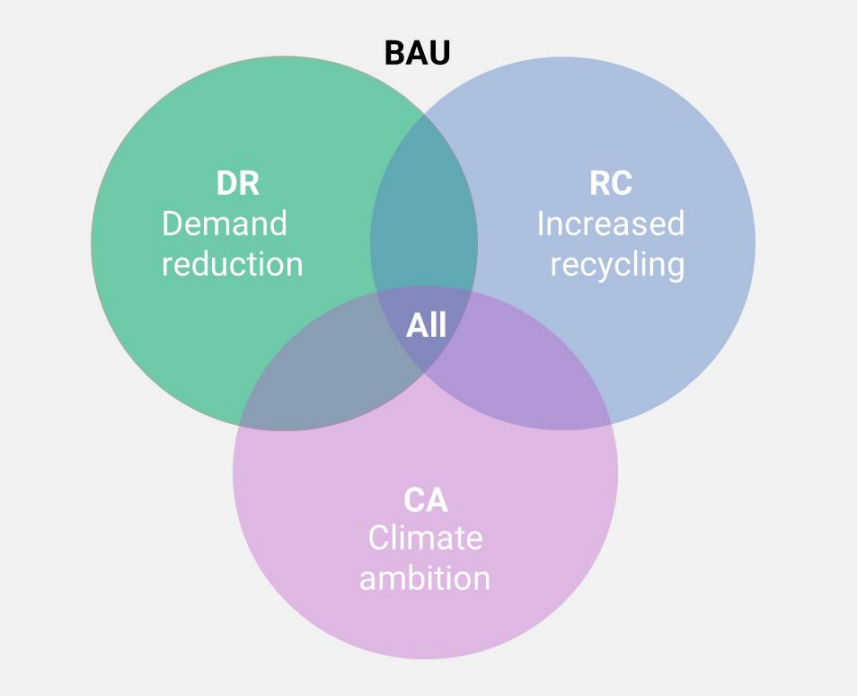


Figure 5: Linking diagram of the scenarios employed in this work.

BAU: Baseline

The baseline scenario assumes the underlying projections as per the SSP2 scenario, and projects that no further climate policies are implemented besides the ones already in place. In this sense, plastics demand increases following historical trends and final disposal options shares remain constant over time.

DR: Demand Reduction

Demand reduction measures for the petrochemical industry can be designed for various end-use sectors. Although plastics materials are used in virtually all economic sectors, plastics are extremely relevant to the packaging sector, which accounts for about 36% of the entire global demand for plastics [54]. In this work, we focus on packaging given several factors. First, packaging alternatives exist for many applications, whereas in other sectors this assumption is not straightforward and would require further analysis to consider material properties and performance. The short-lived nature of plastic packaging also makes it the main contributor to the plastic waste problem, which is the reason why many countries already regulate plastic packaging waste. For instance, the EU passed legislation in 2019 banning single-use plastics,

including plastic cutlery, plates, and straws, by 2021. The legislation also requires producers to contribute to the cost of cleaning up plastic waste and sets a target for member states to recycle 90% of plastic bottles by 2029 [55]. South Korea has established regulatory mechanisms over the packaging sector which includes waste charges and a compulsory recycling ratio of packaging products [56]

Specifically for this work, we focused on reducing the demand for plastics that are destined for the packaging sector in 90% up until 2030 globally. This is a purposedly ambitious assumption to test the changes across the entire supply chain and the limits it imposes to recycling (i.e. waste availability) brought about by demand changes in short-lived plastic use. After 2030, packaging demand remains equivalent to 10% of what it would be in the baseline scenario. The demand for the remaining end-use sectors is unchanged.

In this scenario, we do not apply carbon pricing, assuming that no further climate policy measures are implemented. Moreover, the regional final disposal split remains the same over the century.

RC: Increased Recycling

The increased recycling (RC) scenario assumes that waste management of plastics, consumer awareness, and recycling infrastructure improves worldwide and every region reaches their maximum recycled content in HVC demand by 2060. We assume that every plastic waste generated in year *t* from any end-use sectors can be recycled as an ambitious scenario to test its limits of reducing virgin material.

For this scenario, we assumed that the final disposal split changes to reach regional recycling potential in 2060. Recycling rates increase from 2025 and grow logistically up to 2060 to meet the recycled content potential in HVC demand in each region. The recycled content potential is defined by the following:

$$Rc_{t,R} = \frac{W_{t,R} \times \beta}{D_{t,R}} \quad (2)$$

, where $W_{t,R}$ is the plastic waste available in timestep t and region R, $D_{t,R}$ is the demand for plastics in timestep t and region R, and β is the recycling yield. We assume that HVC demand (i.e., the sum of ethylene, propylene, butadiene, and aromatics demands) and waste are proxies for plastics demand and waste, as a simplification. A recycling yield of 90% was considered as default [57]. This is because in scenarios in which circularity is favored, plastic recycling is prioritized, however a small portion of plastic waste may not be recycled according to the current available technologies or may be contaminated. For this reason, it is realistic to stipulate that approximately 10% of plastic waste can be destined for energy recovery through incineration rather than landfilled [57].

CA: Climate ambitious

In the climate ambitious (CA) scenario, plastic demand and final disposal assumptions remains the same but a carbon pricing compatible with a 1.5 degrees world is implemented based on [58] (see Figure 6). In other words, this scenario corresponds to a world where material efficiency measures are not implemented and emissions reduction in the chemical sector happen only in the supply side, i.e., from oil extraction to plastics production. Demand and final disposal split projections remain unchanged.

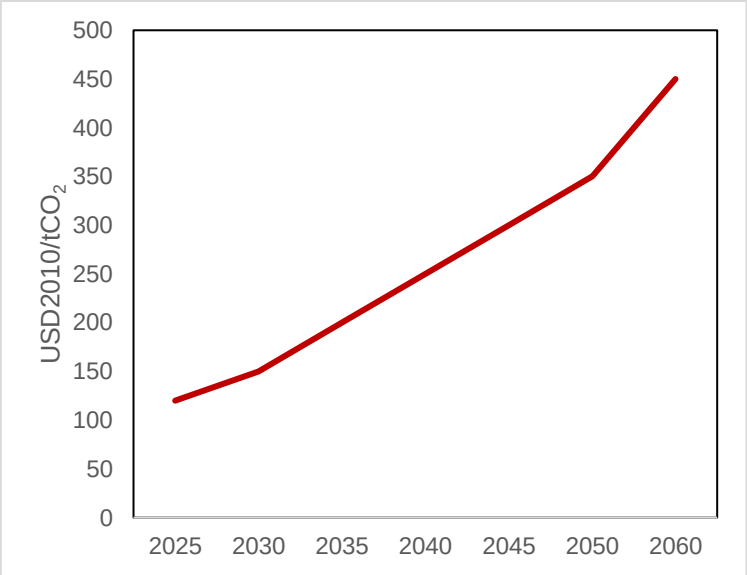


Figure 6. Carbon pricing assumed in carbon constrained scenarios.

Source: adapted from Dietz et al. (2018).

All: Material efficiency and climate policies

The *All* scenario was designed to understand the interrelation of demand reduction, increased recycling, and climate policies in the plastics sector. For that purpose, we implemented all the assumptions in the previous scenarios (i.e., DR, RC, CA).

It is important to stress that this scenario does not result in cumulative emissions reduction from the previous scenarios. For instance, that the availability of waste reduces with packaging demand reduction, which affects the recycled content potentials. Also, demand reduction leads to the reduction of carbon-based feedstock required in the chemicals sector and the burden of the whole system in reducing emissions.

Table 3 - Scenarios description

Scenario	BAU	DR	RC	CA	All
Demand	Demand grows according to regional historical rates	90% reduction of plastic use for packaging by 2030	Demand grows according to regional historical rates	Demand grows according to regional historical rates	90% reduction of plastic use for packaging by 2030
Final disposal	Share of EoL options remain constant over time	Share of EoL options remain constant over time	Mechanical recycling reaches 90% in 2060	Share of EoL options remain constant over time	Mechanical recycling reaches 90% in 2060
Carbon price (2020-2060)	None	None	None	Carbon price consistant with 1.5C budget	Carbon price consistant with 1.5C budget

3. RESULTS

This section will provide the results for the three key steps of this study: 1) regional demand and final disposal scenarios, which were used as inputs to COFFEE with the aim to analyse 2) long-term feedstock and energy use in the chemical sector, as well as 3) its CO_2 emissions.

3.1. Demand and final disposal scenarios

This subsection aims to present the regional HVC demand and final disposal scenarios developed with the aid of a simplified dynamic stock-flow model. These scenarios were exogenously developed and used as inputs in COFFEE.

Figure 7 depicts the results for the baseline (BAU) (a) and demand reduction (DR) (b) scenarios. In the BAU scenario, global HVC demand grows according to historical rates and the share of emerging regions is projected to increase as population and GDP per capita increases (e.g., India, Africa). As for the *DR* scenario, global HVC demand reduces overall up to 2030, but increases later, as the demand growth for end-use sectors other than packaging is unchanged. Therefore, the effect of plastic packaging bans slows down rather than reduces global HVC demand.

Table 4. Recycled content potentials for RE and All scenarios.

	Recycled content potentials in 2060	
scenario	*RE*	*All*
AFR	*52%*	*32%*
AUS	*61%*	*32%*
BRA	*55%*	*46%*
CAM	*67%*	*58%*
CAN	*54%*	*40%*
CAS	*48%*	*30%*
CHN	*62%*	*55%*
EEU	*69%*	*61%*
IND	*54%*	*36%*
JPN	*54%*	*43%*
KOR	*53%*	*39%*
MEA	*53%*	*36%*
RAS	*53%*	*38%*
RUS	*49%*	*42%*
SAF	*55%*	*38%*
SAM	*60%*	*46%*
USA	*59%*	*29%*
WEU	*14%*	*7%*

shows the regional recycled content potentials found for scenarios *RE* and *All* in 2060, which resulted from the plastic dynamic flow-stock model and were used as inputs in COFFEE. The *BAU*, *CA*, and *DR* scenarios assumed that the current final disposal split (Figure 4) remains the same throughout the century. On the other hand, in the *RC* scenario, it was assumed that the maximum recycled content would be achieved in 2060. Lastly, in the *All* scenario, recycled content potentials were limited by the reduction of short-lived plastic demand, which in turn reduced plastic waste availability.

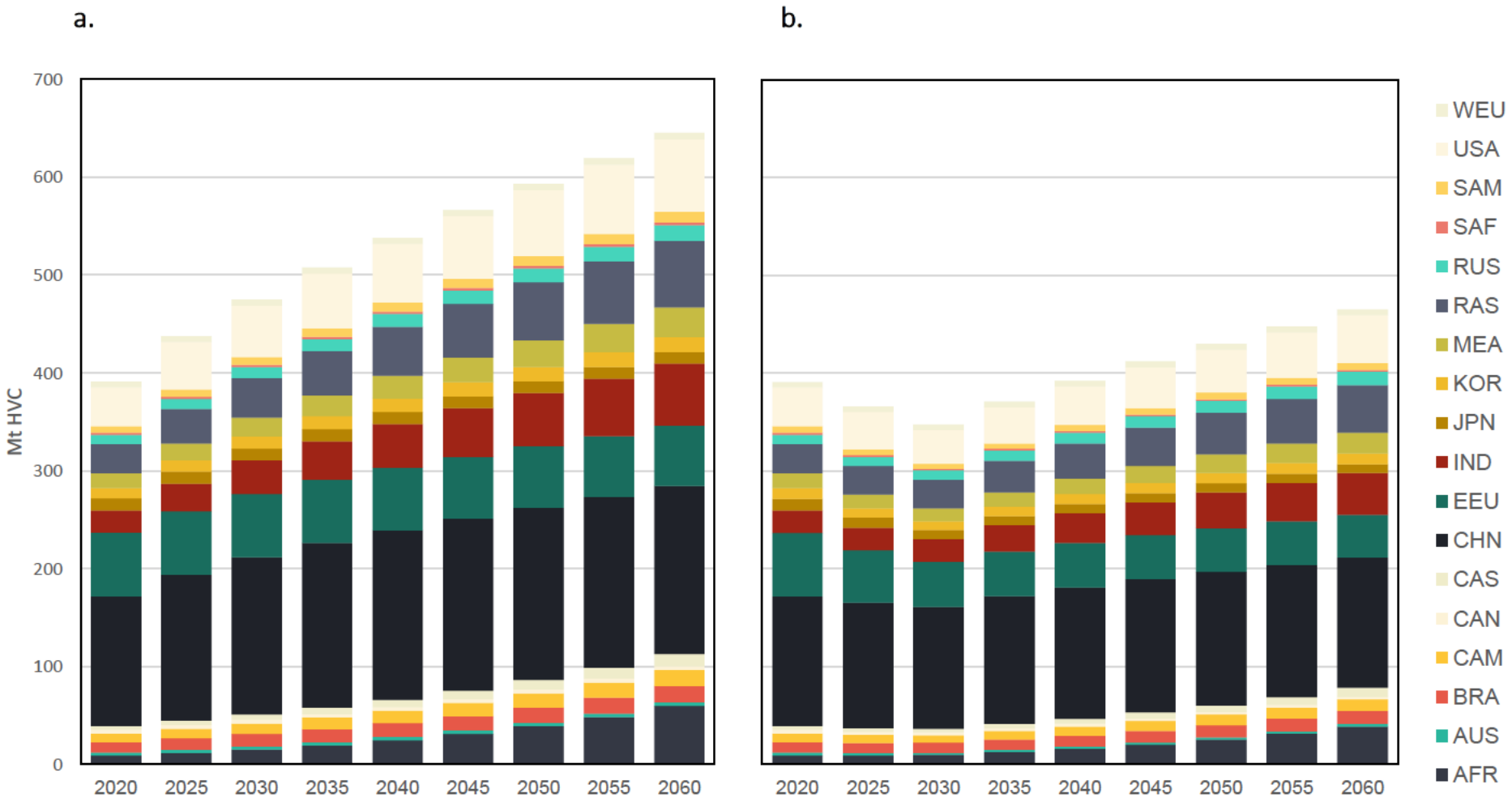


Figure 7. Regional HVC demand for a. baseline and b. demand reduction scenarios.

Table 4. Recycled content potentials for RE and All *scenarios.*

	Recycled content potentials in 2060	
scenario	*RE*	*All*
AFR	*52%*	*32%*
AUS	*61%*	*32%*
BRA	*55%*	*46%*
CAM	*67%*	*58%*
CAN	*54%*	*40%*
CAS	*48%*	*30%*
CHN	*62%*	*55%*
EEU	*69%*	*61%*
IND	*54%*	*36%*
JPN	*54%*	*43%*
KOR	*53%*	*39%*
MEA	*53%*	*36%*
RAS	*53%*	*38%*
RUS	*49%*	*42%*
SAF	*55%*	*38%*
SAM	*60%*	*46%*
USA	*59%*	*29%*
WEU	*14%*	*7%*

3.2. Feedstock and energy use

This subsection presents COFFEE results for global changes in energy use (both for combustion and feedstock purposes) in the chemical[3] sector relative to demand, final disposal, and climate mitigation scenarios (*Figure 8*).

As expected, the *All* scenario leads to highest reduction in final energy use (both combustion and feedstock), indicating the synergistic effect of climate mitigation and material efficiency (i.e., reduce and recycle) policies. Also, biomass use is 1.2EJ (final energy) and 1.6 EJ (feedstock) higher in *CA* than in *All* in 2060, indicating the role of material efficiency in reducing the scale of

[3] The results apply not only to the plastics module, but for the chemicals sector as a whole, i.e., including inorganic and (other) organic chemicals.

production of alternative feedstocks to achieve climate goals, although with a limit since both scenarios heavily rely in bio-based feedstocks.

Oil and gas remain relevant energy and feedstock sources in all of the scenarios assessed up until 2060. That is also valid for coal in those scenarios without climate policy. In *All* and *CA* scenarios, coal used as a feedstock is eliminated before 2040 worldwide.

Scenario *All* reaches the minimum use of fossil fuel as feedstock across scenarios and the use of gas is preferred over naphtha and coal. Also, in all the scenarios assessed, gas use as feedstock increases over time. This indicates that the current trend of using lighter streams such as ethane and LPG as feedstock for chemicals might continue for longer. Considering the higher selectivity of ethane steam cracking to ethylene than for other HVCs, that would mean that on-purpose routes for propylene, butadiene, and BTX would be required to fulfil demands, regardless of material efficiency or climate mitigation measures (see subsection 3.4.).

Furthermore, reducing plastics demand for packaging has a relevant role in reducing feedstock use. However, it reduces up to 20% of total energy use for non-energy purposes, i.e., including other uses such as lubricants, asphalt, fertilizers. Therefore, although plastic packaging demand reduction and recycling are key to reduce emissions for this end-use, the overall impact in non-energy use of fossil fuels is limited. This stresses the need for more ambitious material efficiency measures to tackle carbon lock-in in the non-energy sector for all uses.

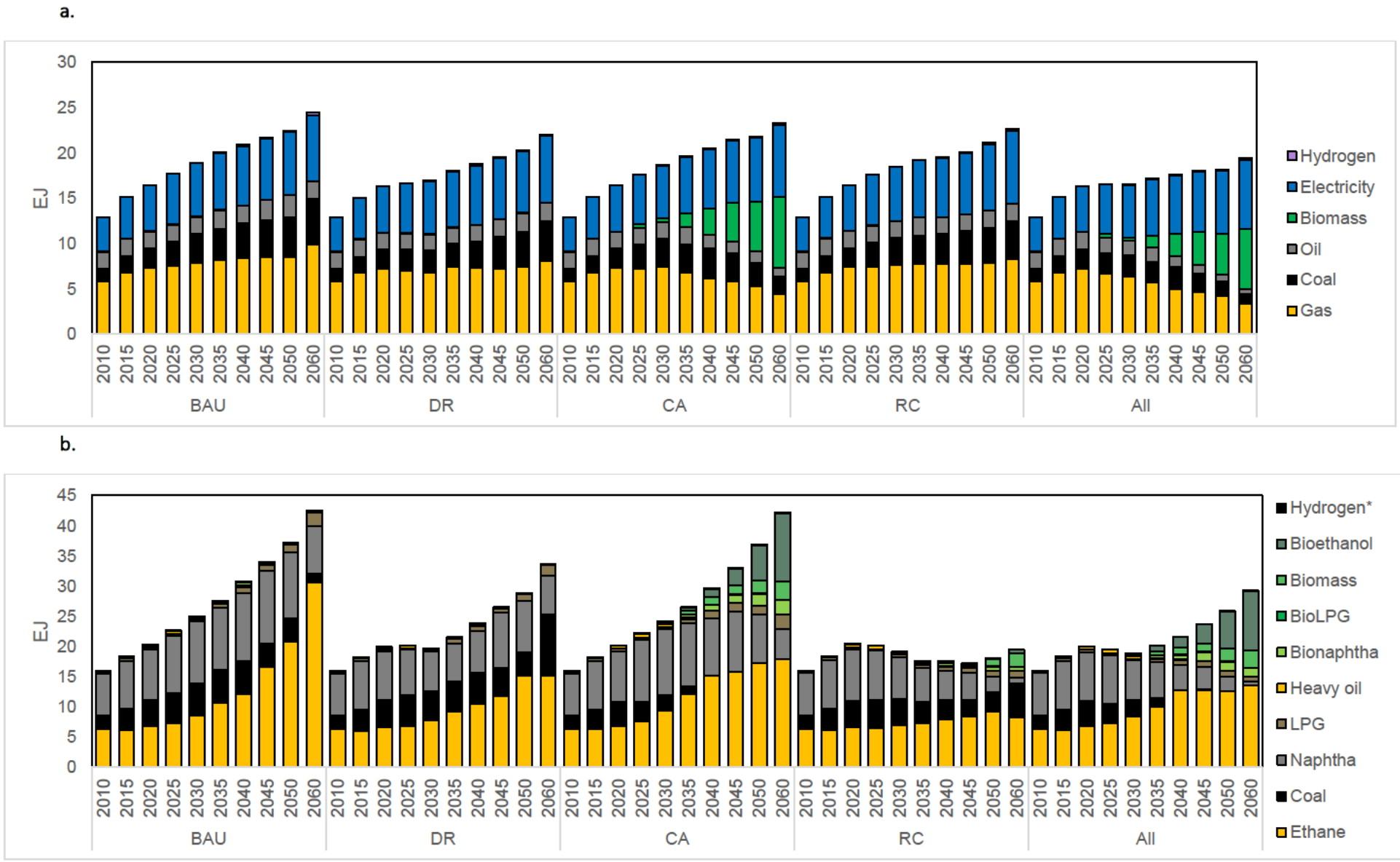


Figure 8. Final energy (a) and feedstock use (b) for BAU, DR, CA, RC, and All scenarios.

3.3. Primary HVC production and CO_2 emissions

This subsection presents COFFEE results for global changes in HVC production and CO_2 emissions in the chemical sector relative to demand, final disposal and climate mitigation scenarios (Figure 9).

Primary HVC production reduces in *DR* in the period 2025-2045 but reaches similar levels to *RC* afterwards. This indicates that, in the long run, promoting recycling is more effective in reducing virgin plastic production. Naturally, the *All* scenario presents the lowest primary production of HVCs, indicating the synergy between increasing circularity and reducing short-lived applications in resource use and emissions reduction. However, it increases in the long run since plastics use in other end-use sectors remain unchanged. This indicates that high and ambitious recycling targets for packaging sector alone are necessary but not sufficient to reduce final energy and emissions in the chemicals sector, thus requiring material efficiency for other end-uses.

Scenario *RC* alone presents an increase in CO_2 emissions. While mechanical recycling of plastic waste does reduce the need for virgin plastic production and thus can reduce energy use and CO_2 emissions associated with plastic production, it still requires a significant amount of energy and resources to collect, sort, and process the plastic waste. Additionally, mechanical recycling can only be done a limited number of times before the quality of the plastic degrades, and it can no longer be used for the same purposes. *RC* scenario thus led to higher emissions than baseline by 2060, although reducing feedstock use.

On the role of demand reduction and recycling in CO_2 emissions, the *All* and *CA* scenarios lead to a net-zero chemical sector by 2050 and 2055, respectively. In both scenarios, recycling is limited. Thus, part of the bio-based materials produced act as carbon sink in landfills or long-lived applications, i.e., infrastructure, which helps to mitigate residual energy emissions.

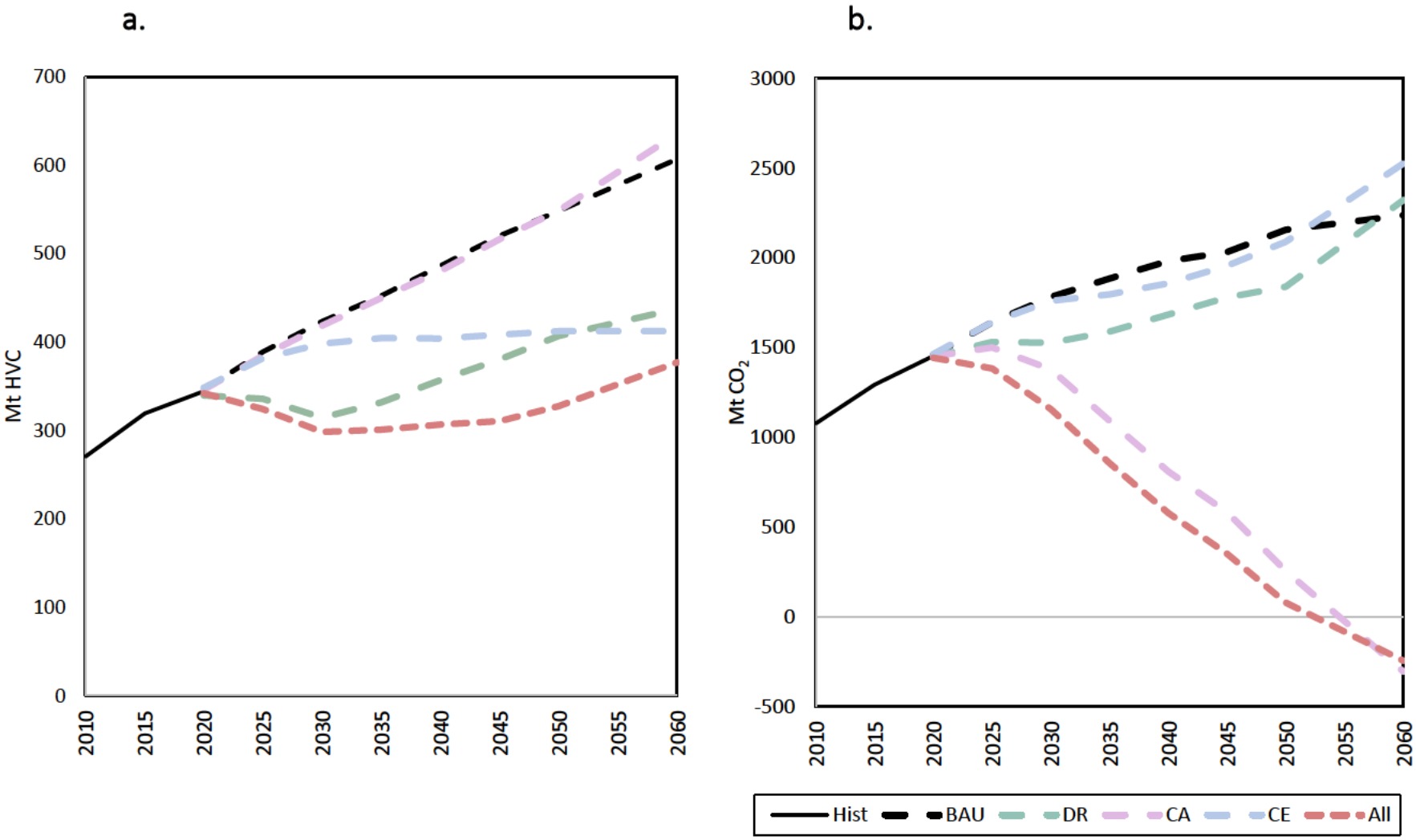


Figure 9. HVC production(a) and CO_2 emissions scenarios

3.4. Technological pathways

This subsection presents COFFEE results for changes in the structure of the global HVC industry, both in terms of technological profile and of feedstock use (Figure 10 and Figure 11).

HVC production is separated by multiproduct, refinery-integrated, and on-purpose facilities. Due to the increasing use of gas in all scenarios, on-purpose routes are required to fill the propylene, butadiene, and aromatics supply gap. This follows a recent trend caused by shift in the refining industry towards lighter feedstocks, i.e., cheap availability of natural gas, when PDH and MTO plants were developed in the Middle East, China and the US to fill the propylene gap.

Also, results show that future chemical demand may extend the lifetime of oil refineries in certain regions even in carbon stringent scenarios. However, reducing demand and increasing recycling can alleviate this effect, thus reducing the share of refinery-integrated production. This suggests that oil refineries are operating with a lower capacity factor. In turn, given their limited flexibility and significant capital investments required to change operations, it is also indicative that less fuel (gasoline, diesel, kerosene) is being produced.

Figure 11 shows that the use of biomass is preferred over CCU as alternative feedstock. This happens due to the non-spontaneous and energy-intensive nature of the CO_2 to hydrocarbons conversion reaction. Plus CO_2 capture costs also pile up and make this alternative less attractive. This is particularly true when carbon pricing is applied, benefiting the supply chain of bio-based feedstocks that perform BECCS. Besides, the development of bio-refineries could play an important role in supplying bio-naphtha in synergy with the provision of low-carbon fuels for hard-to-abate sectors, such as aviation and shipping.

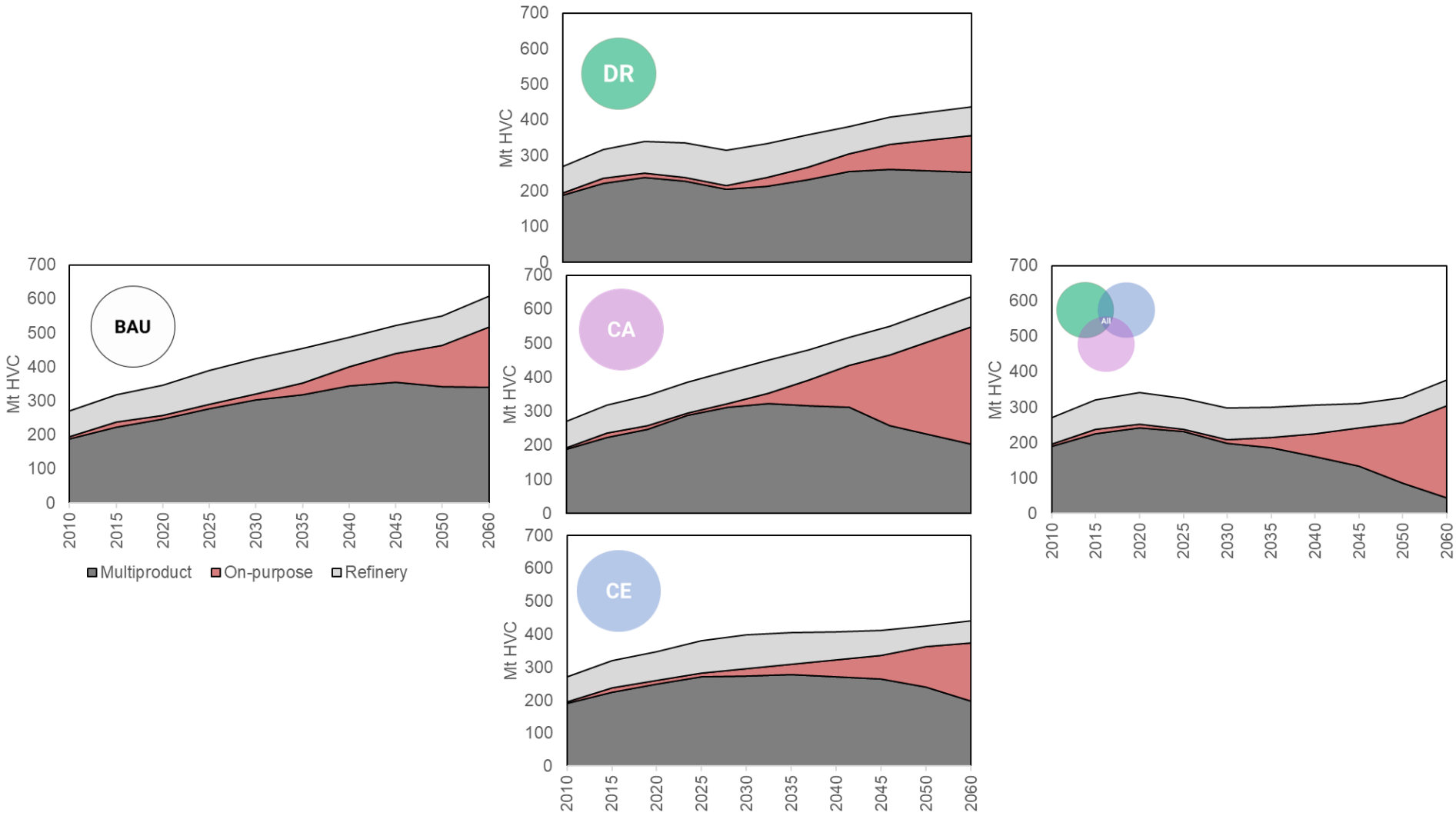


Figure 10. Global HVC production technology profile.

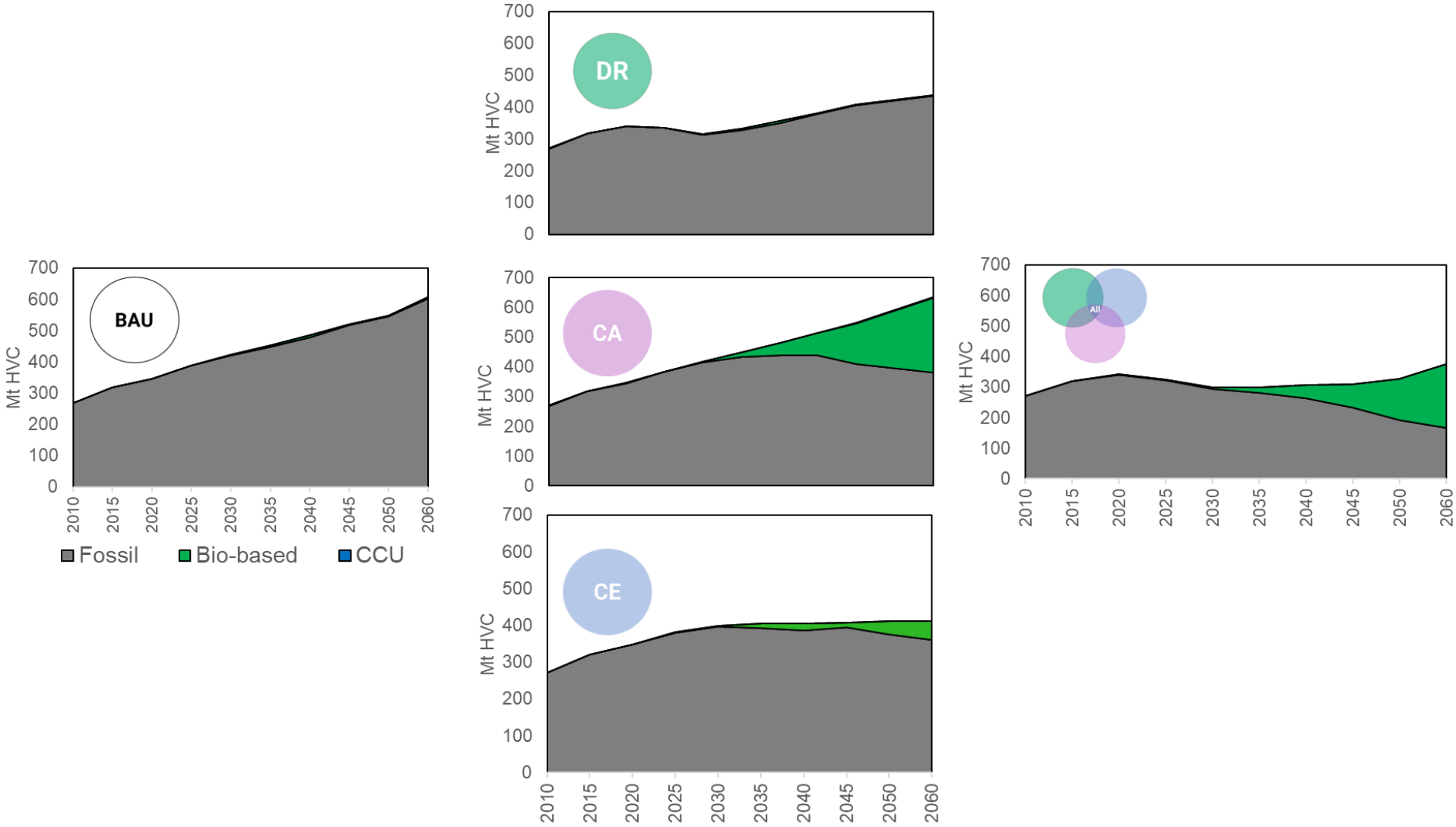


Figure 11. Global HVC production in terms of feedstock type.

4. CONCLUSION

This work aimed to develop a case study in the petrochemical industry to evaluate how climate policies and material efficiency measures affect its carbon mitigation pathways. Specifically, circular economy policies in the petrochemical sector were considered to reduce its final energy needs and contribute to minimize the environmental impacts generated by plastic waste mismanagement.

For this purpose, the petrochemical sector representation within the COFFEE model was improved to be able to incorporate different technology routes and circular economy options. A set of scenarios were built to evaluate how a possible reduction in demand in the packaging sector as well as the possibility of a higher percentage of recycled material can reduce the required final energy input. Furthermore, by modelling routes using biomass, it was also possible to evaluate to what extent biogenic carbon storage in long-lived plastic products can be an efficient measure to tackle climate change.

In this study, ammonia, methanol and high-value chemicals (ethylene, propylene, butadiene and BTX) are referred as organic bulk materials. They are the building blocks in multiple downstream processes that convert them into more complex chemicals for a multitude of material services. While representing fuels use for combustion applications in IAMs is central to assess the climate-related challenges of substituting the main energy source in the world economy, detailing its use for non-energy purposes also helps us to evaluate the implications of substituting fossil fuels in all its pervasiveness in society – as both energy and materials source.

The study showed the importance of oil as a feedstock for high-value chemicals (HVCs) remains in all scenarios, but the reliance on it is expected to decrease with circularity and reduced demand for packaging. Furthermore, the use of bio-based HVCs was also found to be preferred over CCU-based in climate mitigation scenarios due to higher costs of the latter (i.e., carbon capture costs plus highly endothermic reaction).

It is crucial to note that reducing demand or increasing mechanical recycling alone will not be sufficient to reduce emissions and plastic waste. A coupling of demand and circularity strategies is required to achieve climate goals and reduce oil consumption. This approach entails the promotion of numerous material efficiency measures such as the use of reusable packaging, designing packaging for recyclability, and encouraging consumers to reduce their consumption of single-use plastics.

While demand reduction and circularity strategies are necessary, other technologies such as chemical recycling and Crude-to-Chemicals (C2C) can be game-changers in reducing emissions and plastic waste. These technologies were not assessed in this work, but they have the potential to significantly impact climate and energy perspectives in the chemical industry for the next decades. This is mainly because the secondary material that is a product of mechanical recycling has its application limited since inevitably there is a downgrade in its quality. Often, depending on the application, it is necessary to mix virgin material. Therefore, future works need to go deeper into the limitations imposed by recycled material [59].

A few other limitations of this research stem from the simplifications made regarding the obstacles towards circular economy adoption in the petrochemical sector. The use of biomass, for example, is restricted to regional availability that can suffer seasonal fluctuation and interfere with land use dynamics and water consumption. It is therefore extremely necessary to conduct further research on the indirect impacts of biomass use regionally.

In sum, this work has brought new insights on possible ways to decarbonize industries that use fossil fuel for non-energy purposes underpinned by circularity principles. However, unless there is strong legislation, achieving a high percentage of recycled materials can be economically disadvantageous than using virgin material [59]. Therefore, much remains to be explored to determine how to overcome the economic, technical, and socio-cultural barriers that impede the transition to a circular economy.

REFERENCES

[1] IEA, “Extended world energy balances, IEA World Energy Statistics and Balances (database),” 2022.

[2] F. Bauer *et al.*, “Plastics and climate change breaking carbon lock-ins through three mitigation pathways,” *One Earth*, vol. 5, no. 4, pp. 361–376, 2022, doi: 10.1016/j.oneear.2022.03.007.

[3] M. Anshassi, H. Sackles, and T. G. Townsend, “A review of LCA assumptions impacting whether landfilling or incineration results in less greenhouse gas emissions,” *Resour Conserv Recycl*, vol. 174, 2021, doi: 10.1016/j.resconrec.2021.105810.

[4] C. J. Rhodes, “Plastic pollution and potential solutions,” *Sci Prog*, vol. 101, no. 3, pp. 207–260, 2018, doi: 10.3184/003685018X15294876706211.

[5] S. B. Borrelle *et al.*, “Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution,” *Science (1979)*, vol. 369, no. 6509, pp. 1515–1518, Sep. 2020, doi: 10.1126/SCIENCE.ABA3656/SUPPL_FILE/ABA3656-BORRELLE-SM-DATA-S4.CSV.

[6] K. Bucci, M. Tulio, and C. M. Rochman, “What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review,” 2019, doi: 10.1002/eap.2044.

[7] R. Geyer, J. R. Jambeck, and K. L. Law, “Production, use, and fate of all plastics ever made,” *Sci Adv*, vol. 3, no. 7, pp. 25–29, 2017, doi: 10.1126/sciadv.1700782.

[8] L. Lebreton and A. Andrady, “Future scenarios of global plastic waste generation and disposal,” *Palgrave Commun*, vol. 5, no. 1, pp. 1–11, 2019, doi: 10.1057/s41599-018-0212-7.

[9] J. Zheng and S. Suh, “Strategies to reduce the global carbon footprint of plastics,” *Nature Climate Change 2019 9:5*, vol. 9, no. 5, pp. 374–378, Apr. 2019, doi: 10.1038/s41558-019-0459-z.

[10] IEA, “The future of petrochemicals,” *The future of petrochemicals*, 2018, doi: 10.1787/9789264307414-en.

[11] C. C. N. de Oliveira, M. Z. Zotin, P. R. R. Rochedo, and A. Szklo, “Achieving negative emissions in plastics life cycles through the conversion of biomass feedstock,” *Biofuels, Bioproducts and Biorefining*, vol. 15, no. 2, pp. 430–453, 2021, doi: 10.1002/bbb.2165.

[12] V. Daioglou, A. P. C. Faaij, D. Saygin, M. K. Patel, B. Wicke, and D. P. van Vuuren, “Energy demand and emissions of the non-energy sector,” *Energy Environ Sci*, vol. 7, no. 2, pp. 482–498, 2014, doi: 10.1039/c3ee42667j.

[13] P. Stegmann, V. Daioglou, M. Londo, and M. Junginger, “The plastics integrated assessment model (PLAIA): Assessing emission mitigation pathways and circular economy strategies for the plastics sector,” *MethodsX*, vol. 9, 2022, doi: 10.1016/j.mex.2022.101666.

[14] P. Stegmann, V. Daioglou, M. Londo, D. P. van Vuuren, and M. Junginger, “Plastic futures and their CO2 emissions,” *Nature*, vol. 612, no. 7939, pp. 272–276, Dec. 2022, doi: 10.1038/s41586-022-05422-5.

[15] R. Meys, M. Bachmann, B. Winter, C. Zibunas, and S. Suh, “Plastics By a Circular Carbon Economy,” *Science (1979)*, vol. 76, no. October, pp. 71–76, 2021.

[16] X. Sun, M. Xie, L. Mai, and E. Y. Zeng, “Biobased plastic: A plausible solution toward carbon neutrality in plastic industry?,” *J Hazard Mater*, vol. 435, p. 129037, 2022, doi: 10.1016/j.jhazmat.2022.129037 PMID - 35650741.

[17] M. A. E. van Sluisveld, H. S. de Boer, V. Daioglou, A. F. Hof, and D. P. van Vuuren, “A race to zero - Assessing the position of heavy industry in a global net-zero CO2 emissions context,” *Energy and Climate Change*, vol. 2, no. July, p. 100051, 2021, doi: 10.1016/j.egycc.2021.100051.

[18] C. C. N. Oliveira, G. Angelkorte, P. R. R. Rochedo, and A. Szklo, “The role of biomaterials for the energy transition from the lens of a national integrated assessment model,” *Clim Change*, vol. 167, no. 3–4, 2021, doi: 10.1007/s10584-021-03201-1.

[19] P. R. R. Rochedo, “Development of a global integrated energy model to evaluate the Brazilian role in climate change mitigation scenarios,” COPPE/UFRJ, 2016.

[20] A. Gritsevskyi and N. Nakićenovi, “Modeling uncertainty of induced technological change,” *Energy Policy*, vol. 28, no. 13, pp. 907–921, Nov. 2000, doi: 10.1016/S0301-4215(00)00082-3.

[21] S. Messner, M. Strubegger, B. A. mUm, and L. A. ww, “Working Paper User’s Guide for MESSAGE I11 Ffl IlASA International Institute for Applied Systems Analysis A-2361 Laxenburg Austria User’s Guide for MESSAGE I11 FQ! IlASA International Institute for Applied Systems Analysis A-2361 Laxenburg Austria,” 1995.

[22] A. M. Bazzanella, F. Ausfelder, and DECHEMA, “Low carbon energy and feedstock for the European chemical industry,” *The European Chemical Industry Council*, p. 168, 2017, [Online]. Available: www.dechema.de

[23] T. Ren, M. Patel, and K. Blok, “Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes,” *Energy*, vol. 31, no. 4, pp. 425–451, 2006, doi: 10.1016/j.energy.2005.04.001.

[24] TechnipFMC, “Ethylene Production,” vol. 225, pp. 1019–1022, 2017.

[25] T. Ren and M. K. Patel, “Basic petrochemicals from natural gas, coal and biomass: Energy use and CO2 emissions,” *Resour Conserv Recycl*, vol. 53, no. 9, pp. 513–528, 2009, doi: 10.1016/j.resconrec.2009.04.005.

[26] C. N. Eng, S. C. Kang, S. Choi, S. H. Oh, and Y. K. Park, “A Catalytic Cracking Process for Ethylene and Propylene From Paraffin Streams: The Advanced Catalytic Olefins (ACO) Process,” 2007.

[27] G. Chem *et al.*, “Catalytic Cracking of Naphtha into Light Olefins,” vol. 240, no. 1981, p. 2006, 2006.

[28] N. Nesterenko, J. Aguilhon, P. Bodart, D. Minoux, and J. P. Dath, *Methanol to Olefins: An Insight Into Reaction Pathways and Products Formation*. 2016. doi: 10.1016/B978-0-444-63506-8.00006-9.

[29] Flowserve Corporation, “Coal to Olefins (CTO) / Methanol to Olefins (MTO) API Production,” no. December, 2019, [Online]. Available: https://www.flowserve.com/sites/default/files/literature/marketing/fls-1016-asg-eaq.pdf

[30] D. Xiang, S. Yang, Z. Mai, and Y. Qian, “Comparative study of coal, natural gas, and coke-oven gas based methanol to olefins processes in China,” *Comput Chem Eng*, vol. 83, pp. 176–185, 2015, doi: 10.1016/j.compchemeng.2015.03.007.

[31] X. Xu, Y. Liu, F. Zhang, W. Di, and Y. Zhang, “Clean coal technologies in China based on methanol platform,” *Catal Today*, vol. 298, no. December, pp. 61–68, 2017, doi: 10.1016/j.cattod.2017.05.070.

[32] Z. Xu, Y. Zhang, C. Fang, Y. Yu, and T. Ma, “Analysis of China’s olefin industry with a system optimization model – With different scenarios of dynamic oil and coal prices,” *Energy Policy*, vol. 135, no. June, p. 111004, 2019, doi: 10.1016/j.enpol.2019.111004.

[33] H. A. Maddah, “A Comparative Study between Propane Dehydrogenation (PDH) Technologies and Plants in Saudi Arabia,” *American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)*, vol. 45, no. 1, pp. 49–63, 2018, [Online]. Available: http://asrjetsjournal.org/index.php/American_Scientific_Journal/article/view/4244

[34] R. A. Meyers, *CHAPTER 3.3: LIGHT OLEFINS/DIOLEFINS PRODUCTION VIA LUMMUS’S CATOFIN®/CATADIENE® PROCESSES*. McGraw-Hill Education, 2019. Accessed: Jun. 10, 2022. [Online]. Available: https://www.accessengineeringlibrary.com/content/book/9781259643132/chapter/chapter27

[35] Intratec, *Propylene Production via Metathesis - Cost Analysis*. 2012.

[36] R. M. Venner and S. I. Kantorowicz, “Metathesis: Refinery and ethylene plant applications,” *Petroleum Technology Quarterly*, vol. 6, no. 2, pp. 141-142,144, 2001.

[37] S. Farzad, M. A. Mandegari, and J. F. Görgens, “Integrated techno-economic and environmental analysis of butadiene production from biomass,” *Bioresour Technol*, vol. 239, pp. 37–48, 2017, doi: 10.1016/j.biortech.2017.04.130.

[38] F. Guedes, “A MULTI-REGIONAL OPTIMIZATION MODEL FOR THE BRAZILIAN OIL REFINING INDUSTRY,” D.Sc Thesis, Universidade Federal do Rio de Janeiro, 2019.

[39] F. Lantz, V. Saint-Antonin, J.-F. Gruson, W. Suwala Editor, and B. Saveyn, “The OURSE model: Simulating the World Refining Sector to 2030”, doi: 10.2791/73210.

[40] D. Lerede, C. Bustreo, F. Gracceva, M. Saccone, and L. Savoldi, “Techno-economic and environmental characterization of industrial technologies for transparent bottom-up energy modeling,” *Renewable and Sustainable Energy Reviews*, vol. 140, no. January, p. 110742, 2021, doi: 10.1016/j.rser.2021.110742.

[41] IEA, “The Future of Hydrogen,” 2019. doi: 10.1787/1e0514c4-en.

[42] IEA, “The Future of Petrochemicals, Towards more sustainable plastics and fertilisers,” 2018, doi: 10.1016/B978-0-12-394381-1.00002-7.

[43] Y. K. Salkuyeh, B. A. Saville, and H. L. MacLean, “Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes,” *Int J Hydrogen Energy*, vol. 43, no. 20, pp. 9514–9528, 2018, doi: 10.1016/j.ijhydene.2018.04.024.

[44] International Renewable Energy Agency (IRENA), *Renewable Methanol*. 2021. [Online]. Available: http://www.irena.org/

[45] EUROMAP, “Plastics Resin Production and Consumption in 63 Countries Worldwide 2009-2020,” no. October 2016, p. 80, 2016, [Online]. Available: http://www.euromap.org/en/

[46] B. C. O’Neill *et al.*, “The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century,” *Global Environmental Change*, vol. 42, pp. 169–180, Jan. 2017, doi: 10.1016/j.gloenvcha.2015.01.004.

[47] P. G. Levi and J. M. Cullen, “Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products,” *Environ Sci Technol*, vol. 52, no. 4, pp. 1725–1734, 2018, doi: 10.1021/acs.est.7b04573.

[48] P. G. Levi and J. M. Cullen, “Mapping Global Flows of Chemicals: Supporting Information,” *Environ Sci Technol*, 2018.

[49] EPE, “Competitividade do Gás Natural: Estudo de Caso na Indústria de Metanol,” *Informe técnico*, p. 16, 2019, [Online]. Available: http://www.epe.gov.br

[50] L. W. Su, X. R. Li, and Z. Y. Sun, “The consumption, production and transportation of methanol in china: A review,” *Energy Policy*, vol. 63, pp. 130–138, 2013, doi: 10.1016/j.enpol.2013.08.031.

[51] C. Chatterton, “METHANOL AS AN ALTERNATIVE FUEL,” 2018.

[52] OECD and FAO, “OECD-FAO Agricultural Outlook 2021-2030,” 2021.

[53] World Bank Group, *WHAT A WASTE 2.0 - A Global Snapshot of Solid Waste Management to 2050*. Washington, 2018.

[54] F. Bauer *et al.*, “Plastics and climate change breaking carbon lock-ins through three mitigation pathways,” *One Earth*, vol. 5, no. 4, pp. 361–376, 2022, doi: 10.1016/j.oneear.2022.03.007.

[55] EuropeanComission, “SUMMARY OF: Directive 94/62/EC on packaging and packaging waste,” 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:l21207 (accessed Feb. 24, 2023).

[56] O. Fitch-Roy, D. Benson, and D. Monciardini, “All around the world: Assessing optimality in comparative circular economy policy packages,” *J Clean Prod*, vol. 286, p. 125493, 2021, doi: 10.1016/j.jclepro.2020.125493.

[57] P. Morseletto, “Targets for a circular economy,” *Resour Conserv Recycl*, vol. 153, p. 104553, 2020, doi: 10.1016/j.resconrec.2019.104553.

[58] S. Dietz, A. Bowen, B. Doda, A. Gambhir, and R. Warren, “The Economics of 1.5 • C Climate Change,” *Annu Rev Environ Resour*, 2018, doi: 10.1146/annurev-environ.

[59] C. R. Bening, J. T. Pruess, and N. U. Blum, “Towards a circular plastics economy: Interacting barriers and contested solutions for flexible packaging recycling,” *J Clean Prod*, vol. 302, p. 126966, 2021, doi: 10.1016/j.jclepro.2021.126966.

[60] P. R. R. Rochedo *et al.*, “The threat of political bargaining to climate mitigation in Brazil,” *Nat Clim Chang*, vol. 8, no. 8, pp. 695–698, 2018, doi: 10.1038/s41558-018-0213-y.

[61] K. Riahi *et al.*, “The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview,” *Global Environmental Change*, vol. 42, pp. 153–168, 2017, doi: 10.1016/j.gloenvcha.2016.05.009.

[62] MCTIC, “Estimativas de Emissões de Gases de Efeito Estufa no Brasil- 4ª edição 2017,” *Estratégia Nacional De Ciência, Tecnologia E Inovação 2016|2022*, 2017.

[63] BEN, “Balanço Energético Nacional - Brazilian Energy Balance Ministério De Minas E Energia,” p. 292, 2018.

[64] World Bank, “World Bank Indicators,” *Data*, 2013.

[65] IEA, *Energy Statistics of OECD Countries 2011*. 2011. doi: 10.1787/energy_stats_oecd-2015-en.

[66] IEA, *Energy Statistics of non-OECD Countries 2011*. 2011. doi: 10.1787/energy_stats_oecd-2015-en.

[67] H. H. Rogner, “An assessment of world hydrocarbon resources,” *Annual Review of Energy and the Environment*, 1997, doi: 10.1146/annurev.energy.22.1.217.

[68] C. D. Masters, D. H. Root, and E. D. Attanasi, “World petroleum resource assessment and analysis by Basin,” in *World Petroleum Congress Proceedings*, 1994.

[69] USGS, “World Petroleum Assessment 2000,” *USGS World Petroleum Assessment 2000*, 2000.

[70] USGS, “World Petroleum Assessment 2012,” *USGS World Petroleum Assessment 2012*, 2012.

[71] World Energy Council (WEC), “World Energy Resources: 2013 survey,” 2013.

[72] FAO, “Food and Agriculture Organization Statistics Division.,” 2016.

[73] M. Timmer, A. Erumban, J. Francois, and A. Genty, “The World Input-Output Database (WIOD): Contents, Sources and Methods,” *WIOD Background …*, 2012.

[74] C. McGlade, “Uncertainties in the outlook for oil and gas,” 2013.

[75] IEA, “World Energy Outlook 2014,” 2014.

[76] OGJ, “Worldwide Refining Survey,” *Oil & Gas Journal*, 2011.

[77] F. Guedes, “Avaliação De Alternativas Para Redução Do Uso Final De Energia No Setor De Refino De Petróleo Brasileiro E Estimativa De Custos De Abatimento De Emissões De Gases De Efeito Estufa.,” COPPE/UFRJ, 2015.

[78] M. Bender, “An Overview of Industrial Processes for the Production of Olefins – C4 Hydrocarbons,” *ChemBioEng Reviews*, vol. 1, no. 4, pp. 136–147, 2014, doi: 10.1002/cben.201400016.

[79] W. C. White, “Butadiene production process overview,” *Chem Biol Interact*, vol. 166, no. 1–3, pp. 10–14, 2007, doi: 10.1016/j.cbi.2007.01.009.

[80] M. Bender, “Global Aromatics Supply - Today and Tomorrow,” in *New Technologies and Alternative Feedstocks in Petrochemistry and Refining*, 2013, pp. 59–64.

[81] OGJ, “Worldwide Refining Survey,” *Oil & Gas Journal*, 2011.

[82] K. A. Couch, J. P. Glavin, D. A. Wegerer, and J. A. Qafisheh, “FCC propylene production,” *Petroleum Technology Quarterly*, vol. 12, no. 4, pp. 33–43, 2007.

[83] R. Draeger, B. S. L. Cunha, E. Müller-Casseres, P. R. R. Rochedo, A. Szklo, and R. Schaeffer, “Stranded crude oil resources and just transition: Why do crude oil quality, climate ambitions

and land-use emissions matter," *Energy*, p. 124451, Jun. 2022, doi: 10.1016/J.ENERGY.2022.124451.

[84] A. Akah and M. Al-Ghrami, "Maximizing propylene production via FCC technology," *Appl Petrochem Res*, vol. 5, no. 4, pp. 377–392, 2015, doi: 10.1007/s13203-015-0104-3.

[85] IHS Markit, "Crude Oil-to-Chemicals (COTC): A look inside our technology and economic analyses from the 2019-2014 Process and Economics Program (PEP)," 2018. https://cdn.ihs.com/www/pdf/0519/COTCBrochurePEP.pdf

[86] T. Ren, M. K. Patel, and K. Blok, "Steam cracking and methane to olefins: Energy use, CO2 emissions and production costs," *Energy*, vol. 33, no. 5, pp. 817–833, 2008, doi: 10.1016/j.energy.2008.01.002.

[87] T. Ren, B. Daniëls, M. K. Patel, and K. Blok, "Petrochemicals from oil, natural gas, coal and biomass: Production costs in 2030-2050," *Resour Conserv Recycl*, vol. 53, no. 12, pp. 653–663, 2009, doi: 10.1016/j.resconrec.2009.04.016.

[88] OGJ, "INTERNATIONAL SURVEY OF ETHYLENE FROM STEAM CRACKERS — 2015," 2015.

[89] M. Monai and B. M. Weckhuysen, "Propane to olefins tandem catalysis: a selective route towards light olefins production," *Chem Soc Rev*, no. January, 2021, doi: 10.1039/D1CS00357G.

[90] Y. P. Chul, W. Lee, N. Young, and D. S. Park, "Catalytic Cracking of Lower-Valued Hydrocarbons for Producing Light Olefins," pp. 75–84, 2010, doi: 10.1007/s10563-010-9089-1.

[91] K. Van Geem, "Production of bioethylene: Alternatives for green chemicals and polymers," *AIChE Ethylene Producers Conference Proceedings*, pp. 303–313, 2012.

[92] D. Xiang, S. Yang, X. Liu, Z. Mai, and Y. Qian, "Techno-economic performance of the coal-to-olefins process with CCS," *Chemical Engineering Journal*, vol. 240, pp. 45–54, 2014, doi: 10.1016/j.cej.2013.11.051.

[93] M. R. Gogate, "Methanol-to-olefins process technology: current status and future prospects," *Pet Sci Technol*, vol. 37, no. 5, pp. 559–565, 2019, doi: 10.1080/10916466.2018.1555589.

[94] G. Pomalaza, P. Arango Ponton, M. Capron, and F. Dumeignil, "Ethanol-to-butadiene: the reaction and its catalysts," *Catal Sci Technol*, vol. 10, no. 15, pp. 4860–4911, Aug. 2020, doi: 10.1039/D0CY00784F.

[95] "Ullmann's Encyclopedia of Industrial Chemistry," *Ullmann's Encyclopedia of Industrial Chemistry*, Jun. 2000, doi: 10.1002/14356007.

[96] American Chemical Society, "A National Historic Chemical Landmark - The Houdry Process for Catalytic Cracking," 1996, [Online]. Available: https://www.acs.org/content/dam/acsorg/education/whatischemistry/landmarks/houdry/the-houdry-process-catalytic-conversion-commemorative-booklet.pdf

Supplementary Material

S1. Supplementary methods

S1.1. The COFFEE model

The COFFEE (**CO**mputable **F**ramework **F**or **E**nergy and the **E**nvironment) model is a global optimization model of the energy and land use system based on the MESSAGE platform. It is an intertemporal optimization model, in which the optimal solution provides the minimum cost of the global energy system – it does not necessarily reflect the optimal solution for each region individually. This characteristic makes COFFEE an integrated assessment model capable of identifying the indirect effects of the restrictions established in one region (or sector) to the detriment of others. In addition, the model also allows for environmental restrictions, such as limiting GHG emissions, providing an important tool for conducting studies on climate change.

The COFFEE model derives from the combination of a detailed model for Brazil (BLUES)[60] and a global model developed in Rochedo (2016)[19], highlighting Brazil as a separate region, apart from other key regions, like in several global models. The model structure organizes the world in 18 regions, following the representation shown in Figure 12.

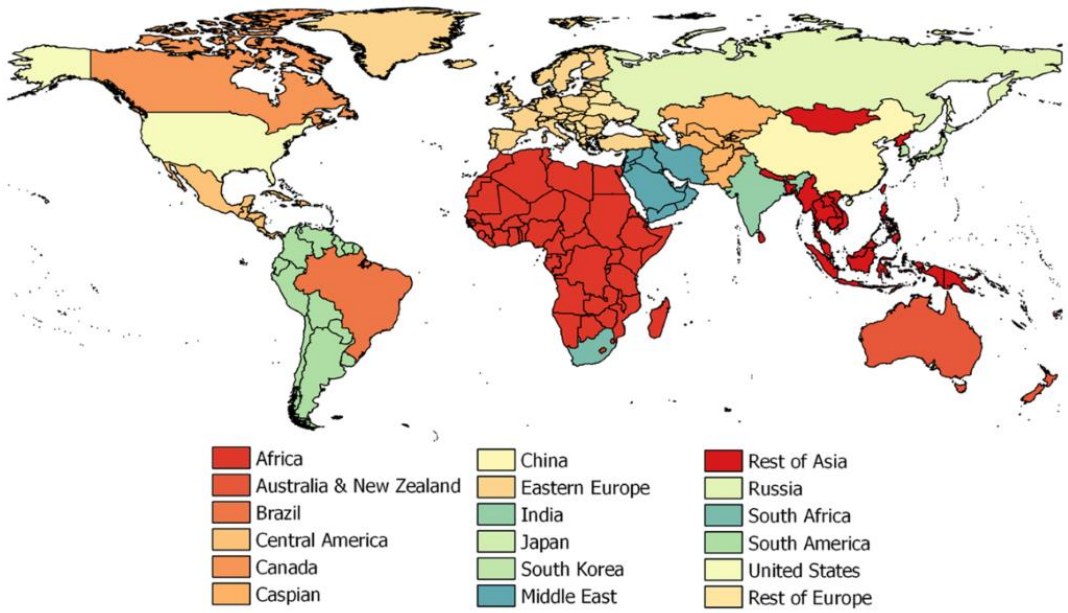


Figure 12: Regional breakdown of COFFEE model

Besides ensuring consistency with the SSP database[61], this structure emphasizes developing countries or economic groups with possible energy and environmental importance in the long run. In this way, they are separated according to their relevance:

- BRICS (Brazil, India, Russia, South Africa and China): economic and energy importance in the future;
- South Korea: future economic importance and core region of future technological innovation;

- USA, European Union and Japan: Current economic importance and energy.

The remaining countries were grouped according to the SSP database[61], with the exception of Pakistan, Indonesia, the countries of Oceania and the countries of Asian plains. Finally, the division involved categorizing 255 countries into the final 18 regions, which are shown in Table 5.

Table 5: COFFEE regions.

Tag	Description
AFR	Africa[a]
AUS	Australia and New Zealand
BRA	Brazil
CAM	Central America
CAN	Canada
CAS	Caspian Region
CHN	China
EEU	East European (EU)
IND	India
JPN	Japan
KOR	South Korea
MEA	Middle East
RAS	Rest of Asia and Oceania
RUS	Russia
SAF	South Africa
SAM	South America[b]
USA	United States
WEU	West Europe

Notes: [a] Excluding South Africa. [b] Excluding Brazil.

It is worth noting that this structure was also a result of the need to address the issue of heterogeneity and access to the necessary information, such as the macroeconomic data, detailed data on the energy sector and consumption profile of these regions. Another feature of the model is that a nineteenth region, containing all the other 18 regions, is added to account for international trade and related GHG emissions.

The Figure 13 shows a simplified representation of the energy chain. Every single region has its own unique resources. Resources include not only deposits of non-renewable energy sources or potential of renewable sources, but also land and reservoir capacity for carbon storage. From the

resources, the energy systems produce all primary energy that is transformed into secondary and, later, into final energy.

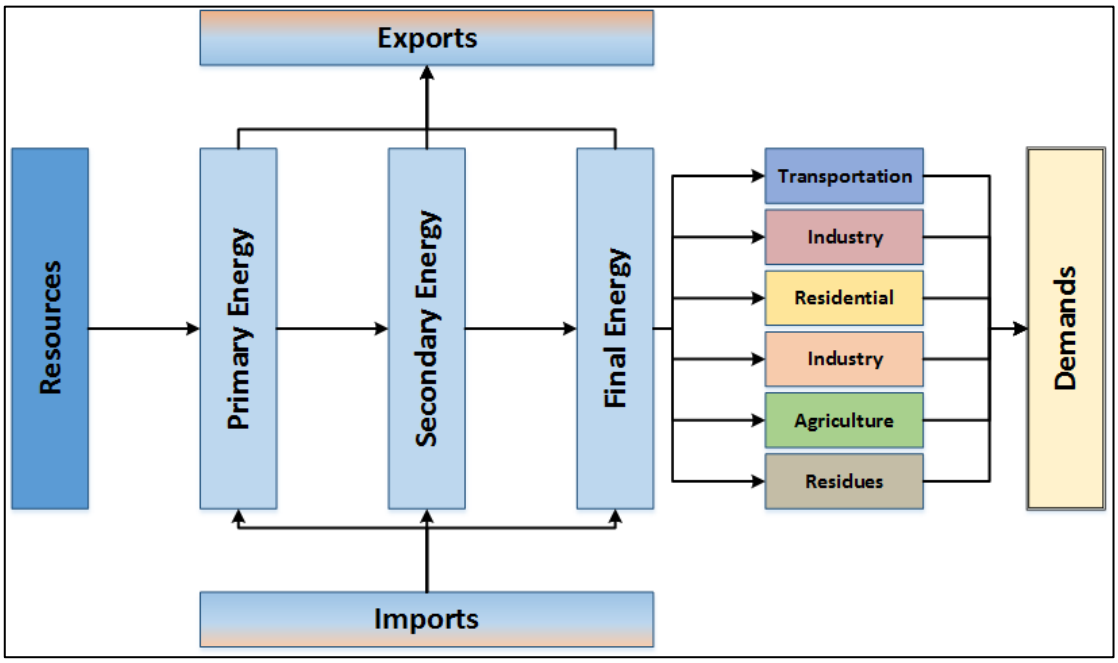


Figure 13: Energy system of the COFFEE model

Once all the necessary energy vectors are either produced, exported or imported, they are transferred into the final consumer sectors. In each sector, all final energy sources are transformed into the necessary energy services. The energy services are the objective of using energy. For instance, the Industry sector can use all sort of energy forms to generate heat, steam, driving force, lightning, cooling, etc. All energy services for each sector are the exogenous demand that the model needs to meet at minimum cost.

Besides the energy systems, another relevant aspect of IAMs is the land use, land use change, forestry and agriculture sector. This sector is strongly linked to climate change by itself, while there is also a strong connection between the land sector and the energy sector. Currently, this is especially true for Brazil, where historically land use emissions are the most relevant aspect of total GHG emissions[62]. Moreover, sugarcane is the second most important source of primary energy in the country, because of ethanol production and cogeneration from bagasse[63].

The approach used for integrating the land system into the energy system is represented in Figure 14. In this simple description, different types of land covers can be modified between one another. In addition, certain type of land covers can be used for agricultural production, in order to meet the demand for food. Furthermore, just as for energy sources, agricultural products can be imported or exported from a single region to another.

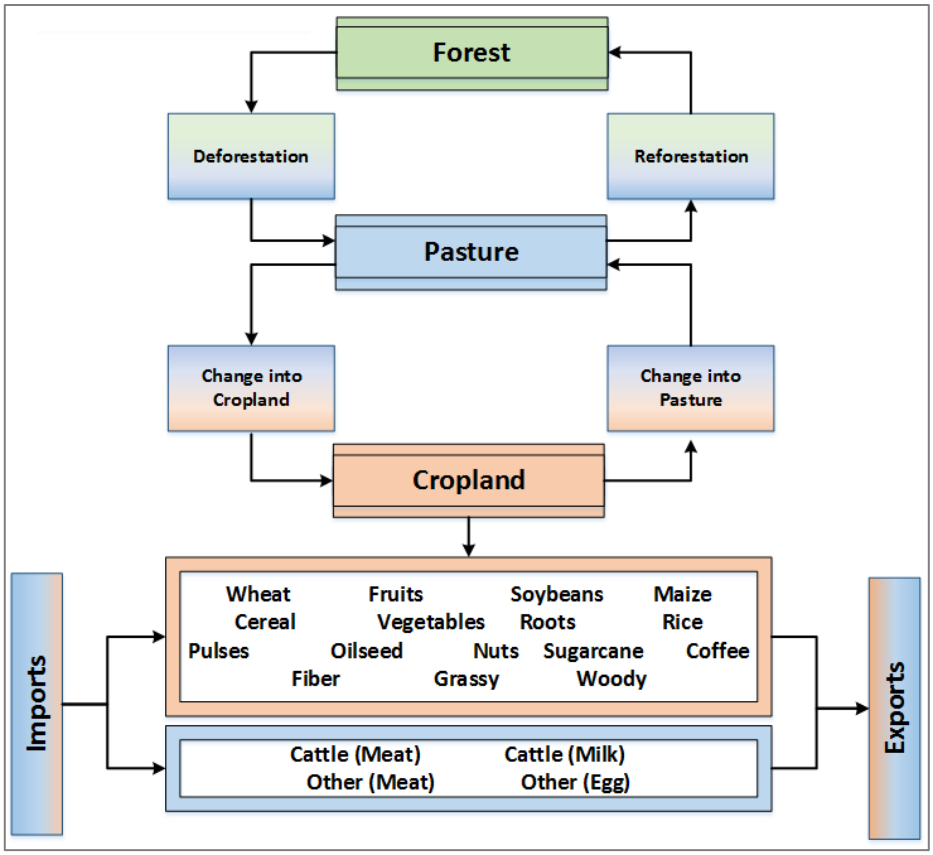


Figure 14: COFFEE land use structure.

In this study, ammonia[4], methanol and high-value chemicals (ethylene, propylene, butadiene and BTX) are referred as organic bulk materials. They are the building blocks in multiple downstream processes that convert them into more complex chemicals for a multitude of material services. While representing fuels use for combustion applications in IAMs is central to assess the climate-related challenges of substituting the main energy source in the world economy, detailing its use for non-energy purposes also helps us to evaluate the implications of substituting fossil fuels in all its pervasiveness in society – as both energy and materials source.

The initial stage of the construction of the model is composed mainly of creating all necessary information for a database. It includes economy, social and energy data for all countries of the world. Several international databases were used, mainly the World Bank[64], reports of energy statistics of OECD and non-OECD by IEA [65], [66] , geological data of energy resources[67]–[71], data for land use and agriculture production from FAO[72] and even microeconomic and macroeconomic data from several countries[73].

This survey allows for the systematic description of the global energy system, and more importantly to adjust the database and the base year. The year 2010 was selected as a base year for the model.

Additional information from this survey includes the description of the regional resources of oil and gas, both conventional and unconventional, coal and uranium. From the quantification of these categories, a global supply curve for each non-renewable resource was developed and compared with that of other studies in the literature (for example, refs [74] and [75]).

[4] Ammonia is strictly an inorganic substance but, since the H_2 source is predominantly fossil fuels (mostly natural gas but also coal and fuel oil), it is included in the organic bulk materials category.

Beyond that, natural resources such as wind, hydro and solar potentials were also estimated using published data for each region, creating the envelope for capacity expansion of renewables in the global energy sector.

In addition to data on the production of resources, information on transformation sector were also compiled. It includes installed capacity and technical description of power plants, CHP plants and the oil refining sector. For instance, the latter was addressed by estimating the capacities of all process units [76] and then using them in the refining simulation tool called CAESAR (Carbon and Energy Strategy Analysis for Refineries), described in ref.[77]. With this tool, the petroleum products production profile and the oil refineries' utilities consumption for each region were estimated, albeit in simplified form.

Another novelty assessment of this study is the detailing and quantification of a reservoir supply curve for the geological storage of carbon dioxide. Through literature data and estimates, it was possible to conjecture a curve that combines the storage potential with the storage costs detailed by reservoir type (such as oil fields, gas and aquifers) and transport distance (ranges below 100, 500, 1,000 and 2,000 km from the source).

In addition to all the data on energy resources and supply, whether electric or fuel, it was also necessary to explore the behavior of energy consumption in the demanding sectors. Thus, the study estimated the demand curves of energy services for the sectors of the economy of each region, as shown in Figure 2.

It is worth noting that the demand for energy services of each of the sectors listed above will directly result from the narratives of socioeconomic scenarios. This fact underscores the importance of quantitative description of SSP scenarios. These same scenarios allow establishing the food demand scenarios that are run along with the scenarios for energy service.

Moreover, the survey and analysis of an extremely high amount of data of different natures (from production and reserves of oil to technical coefficients and consumption profiles) is a highly complex stage, given the heterogeneity of official information available in different countries. However, this step is vital for the proper development of the database, which will be inserted into the global energy model. It is precisely this data that allows for a consistent, representative, and adequate model.

Though COFFEE model well represents energy and land-use systems as described above, a more detailed representation of material production and demand is needed to better assess potential synergies between materials-, energy- and land-use. The following sections provide details on assumptions and data used for representing the industrial sector.

S1.2. Organic bulk materials module

S1.2.1.

In this study, ammonia, methanol and high-value chemicals (ethylene, propylene, butadiene and BTX) are referred as organic bulk materials. They are the building blocks in multiple downstream processes that convert them into more complex chemicals for a multitude of material services. While representing fuels use for combustion applications in IAMs is central to assess the climate-related challenges of substituting the main energy source in the world economy, detailing its use for non-energy purposes also helps us to evaluate the implications of substituting fossil fuels in all its pervasiveness in society – as both energy and materials source.

The following sections provide additional details on technoeconomic parameters and other relevant data of the organic bulk chemicals technologies included in COFFEE.

S1.1.1. High-value chemicals

High Value Chemicals (HVCs) are basic chemicals widely used as building blocks for numerous chemical products.

Ethylene is the primary raw material for the downstream petrochemical industry, and its main derivatives include (high-density, low-density, and linear low-density) polyethylene, ethylene oxide (intermediate for ethylene glycol), ethylene dichloride (precursor of PVC), and ethylbenzene (intermediate of polystyrene - PS), among others. Global ethylene production - approximately 190 Mt/yr – has been steadily growing over the past decades.

Propylene is the second basic chemical in importance, being the building block for several polymers and synthetic fibers such as polypropylene, propylene oxide, acrylonitrile, and others. Global propylene production reached around 130 Mt in 2020.

Butadiene is a linear diolefin produced as a by-product of ethylene with a global production capacity around 11 Mt/yr [78], [79]. It is mostly used for rubbers such as styrene-butadiene rubber (SBR) and polybutadiene (PB), which are essential for tires production, but also acrylonitrile-butadiene-styrene resins (ABS) and other rubbers.

BTX stands for Benzene, Toluene and Xylenes (ortho, meta and para isomers) and global production is approximately of 95 Mt/yr[80]. While p-xylene is mostly used for terephthalic acid production (i.e., PET precursor), benzene applications are more diverse such as for ethylbenzene (for PS production), cumene and cyclohexane, chemicals widely used as solvents, paints, and intermediates. In this study, the terms *aromatics* and BTX are interchangeable.

Thus, by including these products in an IAM, we aim to capture the role of downstream chemicals produced in large scale such as plastics, synthetic fibers and rubbers in future energy and carbon feedstock demand as well as carbon emissions. HVCs technologies are categorized as Refinery co-production, Multiproduct and On-purpose (i.e., facilities dedicated to produce a specific primary chemical, as opposed to steam cracking) to account for potential structural changes that the petrochemical sector may experience due to feedstock transition, climate stringent targets and demand-side transformations. Below, we describe each technology and present the modelling strategy to represent this sector as well as data sources for regional installed capacity in the base year. Techno-economic assumptions for all technologies are also summarized in **Error! Reference source not found.**.

S1.1.1.1. Refinery co-production technologies (FCC-o and CR-o)

A significant share of the global propylene and BTX production is recovered from oil refineries, mainly in gasoline-producing refineries Fluidized Catalytic Cracking (FCC) and Catalytic Reforming (CR) units, respectively. While propylene is recovered diluted in the propane stream in the FCC unit, BTX is produced in Catalytic Reforming unit primarily as an octane rating booster for gasoline but also as a building block for polymers production.

Regional propylene and BTX recovery from FCC and RC were assumed based on country-specific data from the OGJ Worldwide Refining Survey [81]. While aromatics production is explicitly informed in the referred reference, propylene recovery yield in FCC units was assumed to be 5.0 wt% on fresh feed [82].

In the COFFEE model, three refinery schemes (Cracking and Coking, Topping and Hydroskimming, and Hycon), five oil qualities (Light, Medium Sweet, Medium Sour, Heavy, and Extra Heavy) and three operating modes (Kerosene, Diesel and Naphtha runs) are combined to represent current and future

oil resources and reserves, oil derivatives production and refining capacity[83]. To harmonize this with petrochemical co-production, we assume that regional historical rates of propylene and BTX recovery per total atmospheric distillation (ADU) capacity remains constant over time (FCC-o and RC-o, respectively). New refinery capacity with propylene and BTX yields 15% higher than historical were also made available in the model as a simplified and conservative approach to represent the potential increase in refinery-petrochemical integration over time, which could be achieved with e.g. high-severity FCC units and assuming that BTX availability for petrochemical use increases as its demand as a high-octane blend component in the gasoline pool decreases over time [80], [84].
Several Crude-Oil-to-Chemicals (COTC) projects that primarily convert light crude into chemicals are already in stage of development or trial operation – mostly in China (Hengli Petrochemical, Zhejiang Petrochemical, Hengyi Shenghong) and Saudi Arabia (Aramco/SABIC) – with an estimated chemical conversion rate of more than 40% [85]. While an important trend in the petrochemical sector, representing COTC technologies was not possible given the lack of reliable and publicly available data. For now, we are aware that our results on future oil use for non-energy purposes may be underestimated and that refinery-petrochemical integration is a critical topic in the future role of oil and gas that should be addressed in future studies.

S1.1.1.2. Multiproduct technologies

Steam cracking (SC-Naphtha and SC-Ethane)

Steam crackers are at the heart of the petrochemical industry. They break down saturated hydrocarbon streams (ethane, propane, butane, naphtha, and gasoil) into unsaturated compounds such as ethylene, propylene, butadiene, and BTX.

The steam cracking process is a non-catalytic pyrolysis of hydrocarbons, performed under temperatures that go up to 900°C, low pressure (around 1.5 bar) and short residence time (<1s). Under those conditions, carbon-carbon and carbon-hydrogen bonds are broken to make olefins and aromatics.

Steam cracking of lighter streams (i.e., ethane) result in higher relative yields for ethylene whereas heavier streams (i.e., gasoil) yield a more balanced basket of products and fuel-grade by-products (e.g., hydrogen, methane, and butanes) (Figure 15).

Naphtha steam cracking has historically played a central role in producing HVCs. Its use has been more advantageous compared to alternative streams given its higher flexibility to HVCs demand and pricing fluctuations. However, in the past 15 to 20 years the industry has seen a feedstock shift in gas-rich regions to accommodate cheaply available ethane. The Ethylene/Propylene ratio (E/P) of ethane steam cracking is much higher than of other feeds (Figure 15), leading to a significant gap in propylene supply worldwide, especially in Asia. To bridge this propylene gap, several on-purpose technologies were deployed worldwide (e.g, MTO in China, or PDH in the Middle East and in the US).

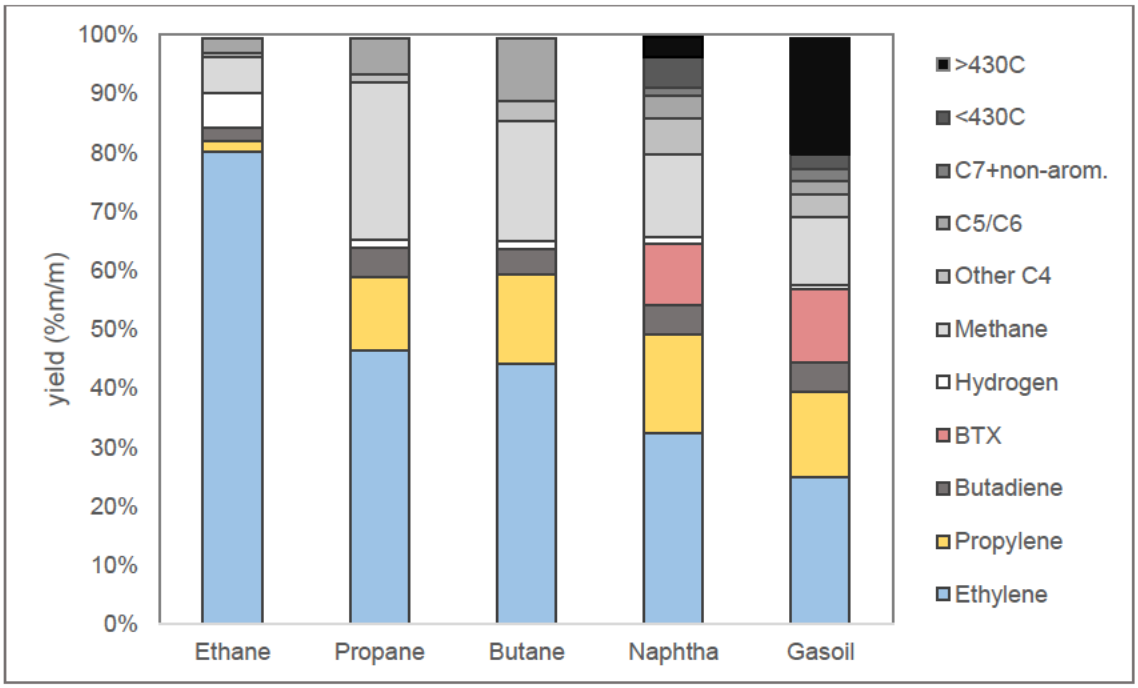


Figure 15 - Steam cracking yields according to feedstock [86], [87].

Data on historical capacity was based on the International Survey Of Ethylene From Steam Crackers (OGJ) [88]. We included only ethane and naphtha steam crackers in the model; propane, butane, and gasoil steam crackers capacity were considered as naphtha steam crackers as a simplification. We consider bionaphtha (e.g., co-product of HVO or SAF production via Fischer–Tropsch synthesis or oligomerization) to be chemically identical to fossil naphtha and, thus, can also be fed into SC-Naphtha.

S1.1.1.3. On-purpose technologies

Propane dehydrogenation (PDH)

Propane dehydrogenation (PDH) is one of the main technologies used so far to bridge the propylene supply gap, mainly in the United States, Middle East, and China. PDH has been available for decades as an alternative to produce polymer-grade propylene with a high selectivity from propane-rich streams and is usually carried out in the presence of a Platinum or Chromium catalyst under low pressure and high temperatures [33]. Bio-propane from bio-LPG streams was also considered as a feedstock. PDH regional historical capacity data was collected from white [89] and grey literature.

Naphtha catalytic cracking (NCC)

Naphtha Catalytic Cracking (NCC) is an alternative steam cracking solution to make up for propylene gap while still using naphtha as feed. While P/E ratio in traditional naphtha steam cracking is around 0.5, NCC can deliver P/E ratios up to 1 with an increase in yield for aromatics as well [26], [42], [90]. By using zeolite catalysts, the overall process not only increases the selectivity to olefins and aromatics but is also more efficient. Only one commercial plant of NCC has been deployed so far in Korea, very similar to a typical FCC unit but designed to produce petrochemicals [26].

Bioethanol dehydration (BDH)

Bioethanol is the most produced biofuel, being predominantly sourced from maize in the US, sugarcane in Brazil, and sugar beet in Europe. As opposed to biodiesel (in relation to conventional diesel), bioethanol is chemically identical to fossil fuel-based ethanol and has been used for energy purposes

in internal combustion engines. Bioethanol dehydration (BDH) to ethylene has been considered a promising technology to decarbonize ethylene production as demand for gasoline and ethanol for passenger transportation decreases in the long term. Braskem deployed a bioethanol dehydration plant of 200kt/yr capacity in 2010 [91]. Also, ethylene can be further oligomerized to bio-jet, green diesel, and bio-naphtha, which makes it compatible with the decarbonization of other hard to abate sectors such as aviation and shipping.

Methanol-to-olefins (MTO)

The methanol-to-olefins (MTO) process is a catalytic conversion process that converts methanol feedstock into light olefins such as ethylene and propylene. The process uses zeolite catalysts in temperatures between 400-500°C and pressures of 0.1-1 MPa to break down methanol molecules into smaller olefin molecules through a series of chemical reactions such as dehydration, cracking, and isomerization. Because of its high selectivity to ethylene and propylene, reduced energy consumption, and lower environmental effect, the MTO process is considered a potential alternative to existing olefin manufacturing processes. Regional historical capacity data was collected from numerous references, with a particular relevance for China, where methanol production is predominantly coal-based [29], [31], [92], [93].

Dimerization (DIM)

In our modeling, we allow for alternative bio-/CCU-based feedstock, but also for using ethylene as a feedstock to other olefins. Dimerization (DIM) is a technology that converts ethylene to 2-butenes and 1-butenes (C4s) thus enabling the conversion of ethylene to propylene through metathesis.

Metathesis (MTT)

Metathesis (MTT) is a process that converts ethylene and 2-butene/1-butene (in our model provided as main output of the dimerization of ethylene and as a co-product in the FCC as well as the PDH processes) for propylene production. Molecules of 1-butene are isomerized to 2-butene, which react with ethylene in the presence of a tungsten oxide catalyst[35]. Stoichiometrically, the reaction produces two molecules of propylene per molecule of ethylene.

Ethanol-to-Butadiene (ETB)

Ethanol-to-Butadiene is being considered as an alternative to butadiene production based on the ethanol platform. Although the reaction mechanism is still under debate, the process generally consists of ethanol dehydrogenation to acetaldehyde, which then reacts with ethanol to form butadiene [37], [94].

Methanol-to-aromatics (MTA)

The methanol-to-aromatics (MTA) process is a catalytic conversion process that transforms methanol into BTX. Much similar to the MTO technology, the process involves several steps, including dehydration, dehydrogenation, and aromatization, but requires higher temperatures (500-700°C) and lower pressures (0.01-0.1 MPa). Furthermore, specialized zeolite catalysts are used to increase the selectivity to aromatics [10], [93].

Catadiene© (CAT)

Catadiene© (CAT) is based on the Houdry process – a catalytic cracking process developed in the early 40s to convert heavy oil fractions to gasoline – and consists of a catalytic dehydrogenation of n-butanes and n-butenes (C4s stream) into butadiene [34], [79], [95], [96].

Catalytic Reforming unit (CR-n)

Conventional catalytic reforming units convert low octane straight run naphtha to gasoline by converting paraffinic and naphthenic compounds into aromatics and thus increasing the octane value of the gasoline stream. In this case, aromatics are produced exclusively for petrochemical production, being fed either by fossil fuel-based or bio-based naphtha. Investment cost assumptions were based on Guedes (2019)[38] and consider not only the cost for the process unit (ISBL) but also direct and indirect costs of the supporting infrastructure for utilities provision, piping, storage and electrical installations, etc (OSBL).

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

EDIT Project Report

Low Emission Scenarios and Energy Consumption Behaviors for Residential Sector in Korea

February 2023

Tae Yong Jung

The Korean Society of Climate Change Research

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1. INTRODUCTION

- EDITS Background

Levels and structure of energy and resource demands are increasingly recognized as a key critical determinants 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 well-being (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

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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 a 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.

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2. Economic and GHG impacts of Low Emission Scenarios

2.1 Introduction

While the supply side, including renewables and other low-carbon technologies, led by rapid technology developments, has been largely focused, there has been growing interest in low energy demand scenarios (LEDS) in recent years. This low-energy demand scenario considers significant changes in lifestyle and human behavior and activities towards low-energy consumption while achieving human wellbeing and sustainable development goals. The reductions in energy demand would reduce the costs and burdens of energy systems to meet the energy demands for providing services. Though its benefits and potential for enhancing mitigation and adaptation, the demand side contains very broad concepts and complexities, which include human behavior, food consumption, and lifestyle, so there have been limited studies on low-energy demand. Moreover, there has been a lot of research on the scenarios for the low energy demands, but analyses on the economic impacts of LEDS are scarce. The study applies a global CGE model and considers low-energy demand scenarios to analyze the economic impacts of LEDS.

2.2 Literature Review

There are an increasing number of studies shedding light on the demand side. The study of Ruijven et al. (2019) showed the importance of considering the future energy demand. It emphasized the energy demand would increase in the future, led by climate change. The study applied econometric estimates of energy demands for electricity, petroleum products and natural gas in agriculture, industry, residential and commercial sectors. This analysis showed that population and economic growth would lead to economic growth in developing countries under SSP scenarios, and the impact of climate change, such as increased frequency of hot days, would further increase energy demands.

Edelenbosch et al. (2020) analyzed the gaps in understanding energy demands by comparing the projections of major IAM models, such as AIM/CGE, GCAM, IMAGE 3.0, and MESSAGE-GLOSBIOM, and reference scenarios. This study applied a

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decomposition analysis and studied the future projections in key sectors, such as building, industry and transport, and reference scenarios. Though the existence of a wide range across models and scenarios, it showed that the population and energy consumption per capita would lead to an increase in emissions in all sectors and scenarios. This study identified the necessity of a deeper dive into energy efficiency and service demand where their projections contain high uncertainties and have great potential to affect emissions in the future.

Scott et al. (2021) investigated how IAMs and the emission scenarios in IPCC 1.5-degree special report considered final energy demand across scenarios and conducted more in-depth studies on energy demand-related assumptions. Although the IAMs provided some information on energy demand projections, the investments in demand-side have not been well-represented and remained highly uncertain. While this study could not find strong evidence of final energy demands' potential to accelerate mitigation to meet global targets, it emphasized that IAMs can be improved by incorporating structural changes leading to energy demand reductions and analyzing policies for reducing energy demands.

Barrett et al. (2022) considered the analysis by Grubler et al. (2018) and applied a bottom-up framework to find the mitigation potential of energy demand reductions, including 'avoid' and 'shift' options, in the United Kingdom. This study analyzed four scenarios with different levels of demand reductions in the agriculture, industry, non-domestic, residential, and transport sectors. This shows a significant near-term mitigation potential to reduce emissions in the UK. Gaur et al. (2022) and Oshiro et al. (2021) applied bottom-up energy modeling (Gaur et al. (2022) used TIMES-Ireland and Oshiro et al. (2021) used AIM/ENDUSE) and analyzed the impact of low-energy demand scenarios with less energy service demands in Ireland and Japan, respectively. Gaur et al. (2022) indicated that lower energy demand would require a smaller energy system and alleviate the cost burden of energy sector transformation. Also, the near-term marginal abatement cost would be largely reduced compared to the BAU pathways. However, this low-energy demand would slow down the technology uptake and fuel switching and lead to a less significant reduction in emissions. Oshiro et al. (2021) considered service demand reductions in the industry, building, and transport sectors and included several measures, including

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dematerialization, the use of multifunctional home appliances, and modal shifts. The study showed that the decrease in energy service demand would affect the energy system changes and reduce the mitigation costs. Lower energy demand would require much less utilization of CCS in power generation and reduce the burdens of energy system transformation, such as earlier retirement of existing fossil-fuel infrastructure and removal of residual emissions.

These studies analyzed how low energy demand scenarios affect each sector or country. Also, they emphasized the necessity of a better understanding of drivers of energy demand and the effects of energy demand reduction policies, and the modeling has the potential to better analyze the demand-side approaches and policies, which have been limitedly considered. While there has been analysis on the mitigation potential of low energy demand, particularly with bottom-up models, the analysis of the economic impacts of low-energy demand scenarios, which specifically reduce energy service demands, with IAMs and top-down CGE models has remained largely untouched.

2.3 Methodology

The computable general equilibrium (CGE) model is a popular methodology for investigating the economic impacts of climate or energy-related policy instruments.
We developed a global multi-regional dynamic CGE model to evaluate the economic and GHG impacts of LEDS.

2.3.1 Data and Assumptions

141 regions of GTAP 10 database are aggregated into 9 regions, composed of 5 SSP regions and four Asian countries, China, India, Japan, and South Korea. The four countries are separated from the corresponding SSP regions to examine more closely the policy implications for some major individual countries.

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Table 1. Regional Classification

Label	Description	GTAP regions code
OECD	OECD (except Japan and South Korea)	ALB, AUS, AUT, BEL, BGR, XER, CAN, CHE, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, GBR, GRC, HRV, HUN, IRL, XEF, ITA, LTU, LUX, LVA, MLT, NLD, NOR, NZL, POL, PRI, PRT, ROU, SVK, SVN, SWE, TUR, USA
ASIA	Asia (except China and India)	XSA, BGD, BRN, XOC, IDN, KHM, LAO, LKA,XEA, XSE, MNG, MYS, NPL, PAK, PHL, SGP, THA, TWN, VNM
LAM	Latin America and Caribbean	XCB, ARG, XCA, BOL, BRA, CHL, COL, CRI, DOM, ECU, GTM, XSM, HND, JAM, MEX, NIC, PAN, PER, PRY, SLV, TTO, URY, VEN, XNA
MAF	Middle East and Africa	XAC, ARE, XEC, BEN, BFA, BHR, BWA, XCF, CIV, CMR, XWF, XNF, EGY, ETH, GHA, GIN, IRN, XWS, ISR, JOR, KEN, KWT, XSC, MAR, MDG, MOZ, MUS, MWI, NAM, NGA, OMN, QAT, RWA, SAU, SEN, TGO, TUN, TZA, UGA, ZMB, ZWE, ZAF, XTW
REF	Eastern Europe and the Former Soviet Union	ARM, AZE, BLR, GEO, KAZ, KGZ, XEE, RUS, TJK, XSU, UKR
CHN	China	CHN
IND	India	IND
JPN	Japan	JPN
KOR	South Korea	KOR

GTAP = Global Trade Analysis Project.
Source(s): Author's own elaboration.

For computational tractability and the convenience of understanding, 76 sectors of the GTAP power database are also aggregated into 13 sectors, where most of the industries are grouped in broader categories while keeping the major energy sectors as detailed as the original GTAP classification. Twelve power sectors of the GTAP power database are aggregated into two, renewable and non-renewable power generation, so that rapid technological development of renewable technologies could be accommodated in the simulation into the distant future.

Table 2. Model Sectors and Global Trade Analysis Project Code

Label	Description	GTAP sectors code
Coa	Coal	Coa
Oil	Oil	Oil
Gas	Natural gas	Gas
P_c	Petroleum and coal product	P_c
Gdt	Gas distribution	Gdt

Agr	Agriculture	PDR, WHT, GRO, V_F, OSD, C_B, PFB, OCR, CTL, OAP, RMK, WOL, FRS, FSH
Ely	Electricity (non-renewable)	NuclearBL, CoalBL, GasBL, OilBL, OtherBL, GasP, OilP, TnD
Ren	Electricity (renewable)	WindBL, HydroBL, HydroP, SolarP
Mfr	Manufacturing	OXT, CMT, OMT, VOL, MIL, PCR, SGR, OFD, B_T, TEX, WAP, LEA, LUM, PPP, CHM, BPH, RPP, NMM, I_S, NFM, FMP, ELE, MVH, OTN, EEQ, OME, OMF
Cnt	Construction	Cnt
Ser	Service	OSG, EDU, HHT, WTR, AFS, TRD, WHS, CMN, OFI, INS, RSA, OBS, ROS
Trn	Transportation	Otp, wtp, atp
Hom	Dwellings	Dwe

Source(s): Author's own elaboration.

The study set the year 2014 as the baseline year since GTAP 10 database provides the year 2014 data as the latest reference year (Aguiar et al. 2019).

The study analyzed how the various mitigation pathways would affect employment. For such analysis, the study used skilled and unskilled labor data from the GTAP 10 database. The GTAP 10 database distinguishes labor into five different types by International Labour Organization occupation: tech/associate professionals, officials/managers/professionals, clerks, service/shop, agricultural, and other workers. The first two types (tech/associate professionals, officials/managers/professionals) are classified as skilled labor, and the remaining three types (clerks service/shop, agricultural, and other workers) are classified as unskilled labor (Corong 2021).

2.3.2 Model Description

A CGE model, which consists of a system of equations, analyzes the interactions among the parts of an economy systemically and solves the equations to find the economy-wide equilibrium (Burfisher 2016). This dynamic recursive CGE model determines each model period. The model equilibrium is the set of equilibrium conditions for all regions and commodities in (i) market equilibrium conditions; (ii) consumption demand functions; (iii) current account balance conditions, budget constraints, and capital stock dynamic equations; (iv) zero-profit conditions; and (v) factor supply functions (Jung et al. 2021). This CGE analysis enables the analysis with policy experiments, which would affect multiple countries and sectors simultaneously.

The CGE analysis results would provide a broad picture of how net zero transitions can benefit or burden developing Asian countries and how their energy choices can affect GHG emissions and climate actions. Based on the results, various policy recommendations will be suggested on how developing economies can promote their economic developments through net zero transitions while constraining the GHG emissions and costs of transitions.

A global multi-regional dynamic recursive CGE model has been constructed for this study. The production function employs a nested constant elasticity of substitution (CES) technology. The nesting structure of the CGE model is designed to resemble OECD ENV-Linkages model (Château et al. 2014).[1] Figure 4 shows the nesting structure of the production technology. Every node of the nest production technologies corresponds to a CES function in calibrated share forms as follows:

$$\boldsymbol{Q} = \overline{\boldsymbol{Q}}\left[\sum_{\boldsymbol{i}} \boldsymbol{\theta_i}\left(\frac{\boldsymbol{X_i}}{\overline{\boldsymbol{X_i}}}\right)^{\boldsymbol{\rho}}\right]^{\mathbf{1}/\boldsymbol{\rho}}, \boldsymbol{\rho} = \frac{\boldsymbol{\sigma}-\mathbf{1}}{\boldsymbol{\sigma}},$$

where Q is the amount of output and the Xi is the i-th input. $\boldsymbol{\sigma}$ is the constant elasticity of substitution between inputs and the upper bars indicate the base year values. $\boldsymbol{\theta_i}$ is the value share of i-th input. The equilibrium conditions to the CES technologies are as follows:

$$\boldsymbol{X_i} = \boldsymbol{\lambda_i^{\sigma-1}\theta_i}\left(\frac{\overline{\boldsymbol{\beta}}}{\overline{\boldsymbol{P_i}}}\right)^{\mathbf{1}-\boldsymbol{\sigma}}\left(\frac{\boldsymbol{\beta}}{\boldsymbol{P_i}}\right)^{\boldsymbol{\sigma}} Q, \boldsymbol{\beta} = \overline{\boldsymbol{\beta}}\left[\sum_{\boldsymbol{i}} \boldsymbol{\theta_i}\left(\frac{\boldsymbol{P_i}}{\overline{\boldsymbol{P_i}}}\right)^{\mathbf{1}-\boldsymbol{\sigma}}\right]^{\mathbf{1}/(\mathbf{1}-\boldsymbol{\sigma})},$$

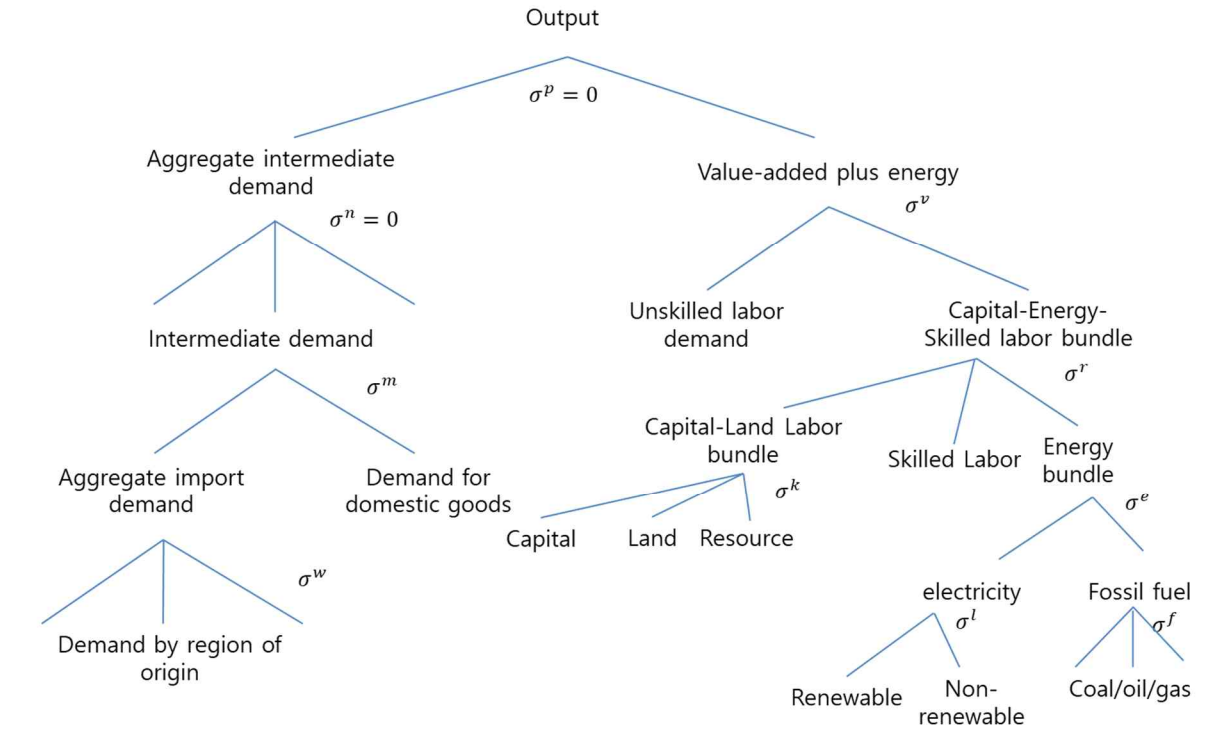
where P_i is the price of i-th input and β is the output price.

The set of equilibrium conditions described above applies to all the CES technologies, including all the sub-nodes of the nested CES functions and other relationships such as substitution between domestic versus imported goods, transformation between domestic versus export demands, and competitions among regions for international transport services.

[1] The CGE model for this study is a modified version of the KEI-Linkages model, which is developed based on OECD Linkages model. The KEI-Linkages model has been applied for a range of climate policy analyses: refer to Lim and Kim (2012) and Koo et al. (2019) for previous studies.

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Figure 1. Nesting Structure



Source: Author's own elaboration.

Dynamic recursive CGE models find equilibria period-by-period instead of searching the one-shot decision for the entire time horizon. Households make instantaneous decisions, but the model's dynamic structure continues to accumulate physical capital, which becomes a part of the future production process.

The Armington specification is applied to the international trade block by using a two-level nested CES structure. At the top nest, the optimal combination of the domestically produced goods and aggregate imported goods was determined by domestic agents, and, at the subsequent nest, the agents allocate demand for the aggregate import across the trading partners (Jung et al. 2021).

The Cobb-Douglas utility is assumed for the household. The government collects a variety of taxes, such as income taxes, factor taxes, consumption taxes, and tariffs, and makes consumption decisions based on the Cobb-Douglas production function, while its aggregate level is fixed to be a constant share of the real GDP. The government budget surplus/deficit is set at its base year level,ss and the income tax

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rates are adjusted endogenously accordingly. The current account surplus/deficit of each region is also assumed to be constant at its base year level.

Table 3: Selected Key Equations of the Computable General Equilibrium Model

Capital stock dynamics	$K_t = (1-\delta)^k K_{t-k} + \frac{(1+g_I)^k - (1-\delta)^k}{g_I + \delta} I_{t-k}$
Current account balance	$\sum_{(r',i)} Pfob_{r,r',i} Qtrade_{r,r',i} + \sum_i Ptmserv_{r,i} Qtmserv_{r,i} + ForegnSaving_r = \sum_{(r',i)} Pcif_{r',r,i} Qtrade_{r',r,i}$
Budget balance (household, government, and investment)	· $(1-ti)\cdot\sum_f PF_f QF_f = \sum_i P_i \cdot (1+tc_i)\cdot QC_i + HSaving$ · $\sum_f tf_f PF_f QF_f + ti\sum_f PF_f QF_f + \sum_i (tc_i P_i QC_i + tp_i PP_i QP_i + \sum_j t_{ij} P_i QAP_{ij}) + \sum_{(r',i)} tariff_{r',r,i} Qtrade_{r',r,i} = \sum_i P_i QG_i + GovSaving$ · $\sum_i P_i QINV_i = HSaving + GovSaving + ForeignSaving$

k: step size for simulation (set to 2 years)
K_t: Capital stock at period *t*
δ: Capital depreciation rate
I_t : Aggregate investment at period *t*
g_I: Growth rate of investment
$Pfob_{r,r',i}$: FOB price of commodity *i* traded from *r* to *r'*
$Pcif_{r,r',i}$: CIF price of commodity *i* traded from *r* to *r'*
$Qtrade_{r,r',i}$: Volume of commodity *i* traded from *r* to *r'*
$tariff_{r,r',i}$: Import tariff rate on commodity *i* traded from *r* to *r'*
$Ptmserv_{r,i}$: Price of international transport service *i* provided by region *r*
$Qtmserv_{r,i}$: Quantity of international transport service *i* provided by region *r*
PF_f: Price of factor *f*
QF_f: Quantity of supply of factor *f*
P_i: Price of commodity *i*
QC_i: Household consumption of commodity *i*
QP_i: Production volume of commodity *i*
QAP_{ij} : Intermediate consumption of commodity *i* in sector *j*
PP_i: Output price of commodity *i*
QG_i: Government consumption of commodity *i*
$QINV_i$: Investment consumption of commodity *i*
ti : Income tax rate for household
tc_i: Consumption tax rate for commodity *i*
tf_f: Tax rate for factor *f*
tp_i: Output tax rate for commodity *i*

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t_{ij} : Intermediate consumption tax rate for commodity *i* in sector *j* *HSaving* : Household saving *GovSaving* : Government saving *ForeignSaving* : Foreign saving

CIF = cost, insurance, and freight (importer's margin-inclusive price), FOB = free on board.

Source(s): Author's own elaboration.

The authors utilized the GTAP 10 database to establish a Global Social Accounting Matrix, which is a key input data for CGE analysis (Aguiar et al. 2019), and the model used UN Population projections and IPCC SSP2 scenario for model calibration. The model is calibrated by adjusting total factor productivity to reproduce the SSP2 GDP projection. The learning rate of 15% is applied to the productivity of renewable energy technology.

While the dynamic CGE model can provide various scenario analyses and implications on the impacts of net zero transition on global economies and employment, this methodology has a few limitations. In general, the CGE model assumes a constant elasticity of substitution and contains rigidities in production and trade structures, so it is limited to incorporate the changes in elasticities of substitution led by various drivers. Assuming non-changing parameters, including elasticities of substitution, over a long time horizon may not reflect the possibilities of changes in those parameters in the future. Moreover, it is limited to incorporate emerging new industries or technologies, such as hydrogen, with very limited available information. Last, the model is based on a somewhat outdated Global Social Accounting Matrix built on GTAP 10 database. Although GTAP 10 database is the most up-to-date, extensive database for establishing the Global Social Accounting Matrix for global CGE analysis, the IO table provided by GTAP 10 database is somewhat outdated as its reference year is 2014, which would not properly reflect the global economy today.

2.4 Scenarios

We construct LEDS with changing assumptions on the energy consumption behaviors of households and industries. We design not only LEDS but also other related scenarios to look at the interactions between different policies and behavioral/technological changes. We selected three kinds of scenarios on policies or

behavioral/technological changes. The first scenario (‘Ctax’) is a carbon pricing scenario where a carbon tax is levied all sources of CO2 emissions, whether from industry or from households. We assumed the carbon price trajectory that the carbon tax rates increase linearly from 0 in 2020 to 100 USD/tCO2 by 2030 and further increase towards 250 USD/tCO2 by 2050. This trajectory is suggested by IEA in the Net Zero Pathway for the global energy sector.

The second scenario (‘Led’) is Low Energy Demand Scenario (LEDS), where the energy consumption behavior is assumed to be changing towards lower consumption. Technically, we assume the share parameters of CES nest are composed of energy bundle, capital-land-resource bundle, and skilled labor bundle. We decreased the share parameter for energy bundle by 1% each year from 2023 and adjusted the share parameter for the other two input bundles so as to keep the sum of share parameters for this node equals one. This assumption effectively operationalizes the behavioral/technological changes for LEDS by reducing the demand for energy bundles in all the industrial sectors and the household.
The third scenario (‘Eff’) is the Energy Efficiency scenario, where the autonomous energy efficiency improvement (AEEI) occurs in all the industrial sectors as well as in the household. Technically, efficiency parameters for energy input bundle increase by 1% per year in all the industrial sectors and the household.

We develop three more scenarios that combine two of the above three scenarios: CtaxLed for Ctax plus Led scenario, LedEff for Led plus Eff scenario, and CtaxEff for Ctax plus Eff scenario. We construct one more scenario (‘CtLeEf’) with combining all three kinds of scenarios to see the composite effects of the three different policy and behavioral assumptions. We establish the baseline scenario (‘BAU’) as business-as-usual case with no specific assumptions on mitigation regulation or behavioral/technological changes. The BAU scenario will be the benchmark with which to evaluate the impacts of all the scenarios developed.

Table 4.Description of Scenarios

Scenario	Key assumptions
BAU	Baseline scenario GDP forecasts in SSP2 scenarios by OECD
Ctax	Carbon tax on all CO2 emissions from 2021

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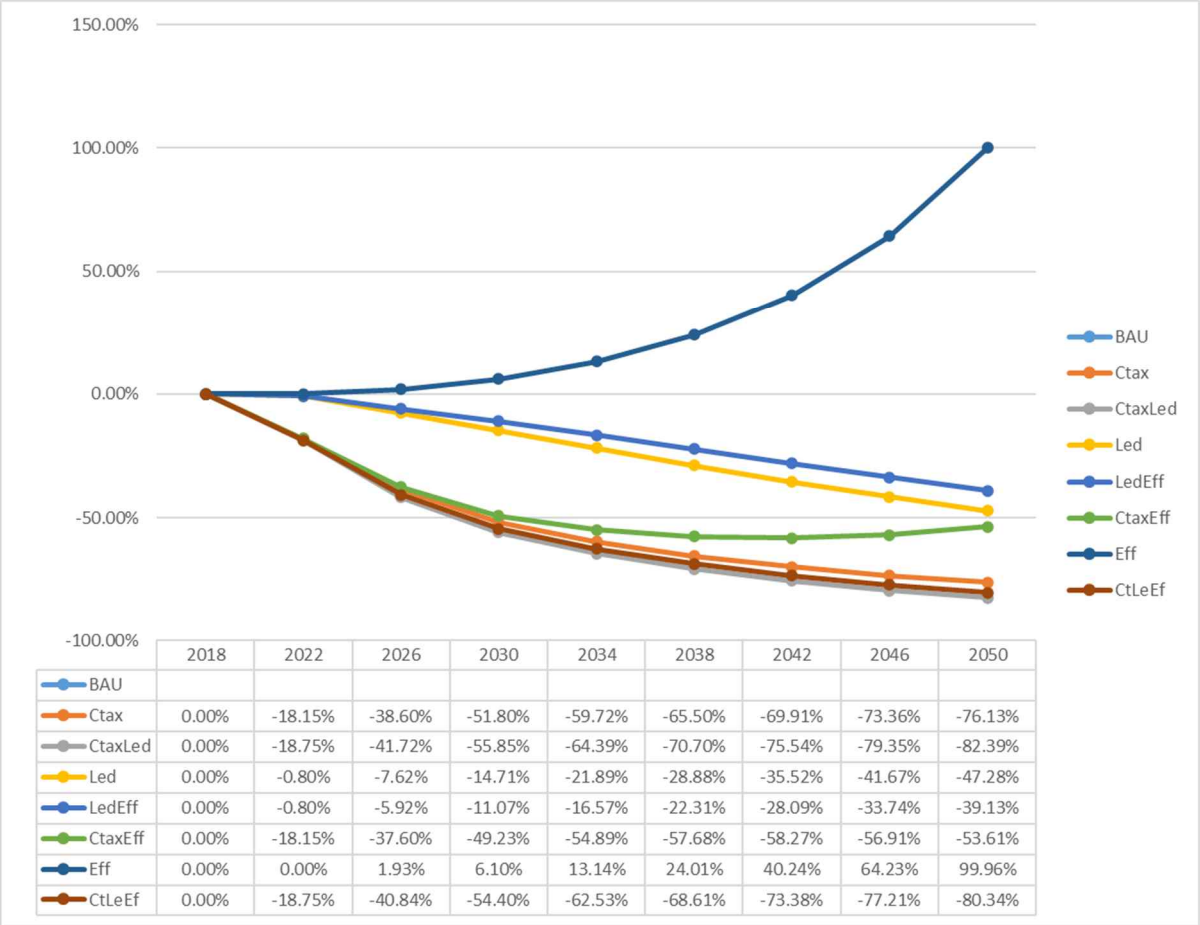
	Linear increase of carbon tax rates from 0 to 100 USD/tCO2 in 2030 and to 250 USD/tCO2 in 2050 Tax revenues are used to reduce labor taxes
Led	Low Energy Demand Scenario (LEDS) Share parameters of energy bundle decrease by 1 % per annum from 2023
Eff	Energy Efficiency scenario Efficiency of the energy input bundle increases by 1 % per annum from 2023
CtaxLed	Combination of Ctax and Led scenarios
LedEff	Combination of Led and Eff scenarios
CtaxEff	Combination of Ctax and Eff scenarios
CtLeEf	Combination of Ctax, Led and Eff scenarios

2.5 Results

Figure 2 shows the impacts on CO2 emission of the scenarios designed above. The energy efficiency scenario ('Eff') shows a rapid increase of emissions over BAU, while all the other scenarios show reductions in CO2 emission. This indicates that energy efficiency improvement, without supplementary policy measures or behavioral changes, might lead to the increase, rather than decrease, of emissions. This is due to the rebound effect of energy consumption: While more efficient energy technologies may reduce the energy demands for the production of various outputs, such lower demand for energy decreases the price of energies, which will promote bigger consumption of energies and furthermore higher consumption of energy-intensive products which become less expensive due the lower energy prices. Another interesting observation from the results is that the emission increase from energy efficiency improvement is dramatically reduced and turned into significant emission reductions if combined with carbon pricing or behavioral changes towards low energy demands.

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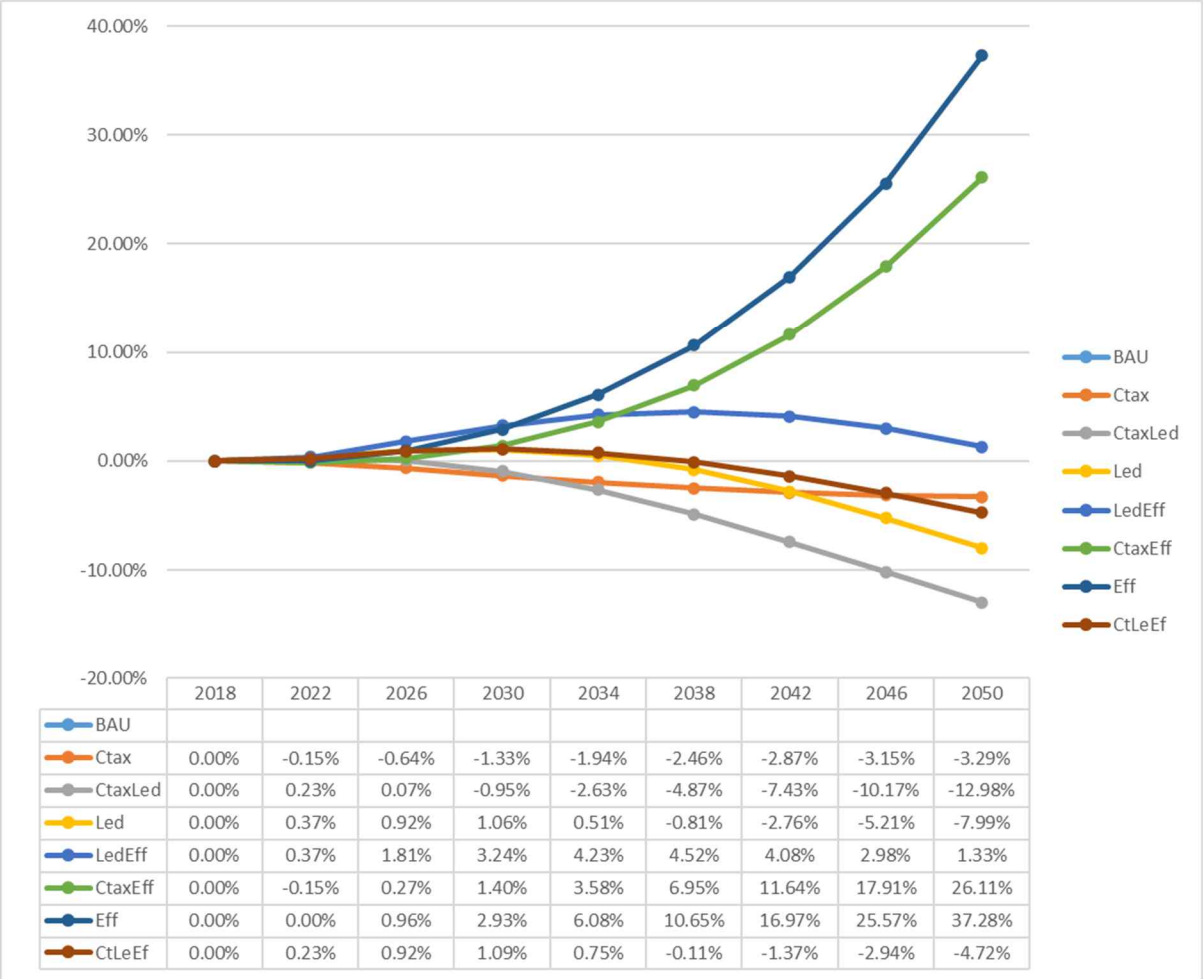
Figure 2. CO2 Emission changes from BAU



	2018	2022	2026	2030	2034	2038	2042	2046	2050
BAU									
Ctax	0.00%	-18.15%	-38.60%	-51.80%	-59.72%	-65.50%	-69.91%	-73.36%	-76.13%
CtaxLed	0.00%	-18.75%	-41.72%	-55.85%	-64.39%	-70.70%	-75.54%	-79.35%	-82.39%
Led	0.00%	-0.80%	-7.62%	-14.71%	-21.89%	-28.88%	-35.52%	-41.67%	-47.28%
LedEff	0.00%	-0.80%	-5.92%	-11.07%	-16.57%	-22.31%	-28.09%	-33.74%	-39.13%
CtaxEff	0.00%	-18.15%	-37.60%	-49.23%	-54.89%	-57.68%	-58.27%	-56.91%	-53.61%
Eff	0.00%	0.00%	1.93%	6.10%	13.14%	24.01%	40.24%	64.23%	99.96%
CtLeEf	0.00%	-18.75%	-40.84%	-54.40%	-62.53%	-68.61%	-73.38%	-77.21%	-80.34%

The figure below shows the impacts on the real GDP of the seven scenarios. The impacts on real GDP are positive in three scenarios of ‘Eff’, ‘CtaxEff’ and ‘LedEff’, while all the other scenarios results in negative impacts. The carbon pricing and LEDS scenario lead to negative effects on real GDP, but if combined with energy efficiency improvements, affect real GDP positively. It is notable that LEDS scenario accompanies a significant reduction of real GDP and the rate of reduction is bigger than that of carbon pricing scenario. If combined with energy efficiency improvements, the carbon pricing scenario (‘CtaxEff’) mitigates most of its negative impacts on real GDP and attains almost full potential benefits under the energy efficiency scenario (‘Eff‘) but the LEDS (‘LedEff’) does not.

Figure 3. Real GDP changes from BAU



	2018	2022	2026	2030	2034	2038	2042	2046	2050
BAU									
Ctax	0.00%	-0.15%	-0.64%	-1.33%	-1.94%	-2.46%	-2.87%	-3.15%	-3.29%
CtaxLed	0.00%	0.23%	0.07%	-0.95%	-2.63%	-4.87%	-7.43%	-10.17%	-12.98%
Led	0.00%	0.37%	0.92%	1.06%	0.51%	-0.81%	-2.76%	-5.21%	-7.99%
LedEff	0.00%	0.37%	1.81%	3.24%	4.23%	4.52%	4.08%	2.98%	1.33%
CtaxEff	0.00%	-0.15%	0.27%	1.40%	3.58%	6.95%	11.64%	17.91%	26.11%
Eff	0.00%	0.00%	0.96%	2.93%	6.08%	10.65%	16.97%	25.57%	37.28%
CtLeEf	0.00%	0.23%	0.92%	1.09%	0.75%	-0.11%	-1.37%	-2.94%	-4.72%

We can see the different directions and scales of impacts on real GDP and CO2. LEDS and carbon pricing scenarios show significant reductions of CO2 with negative impacts on real GDP, while Energy Efficiency scenario results in huge increase of CO2 emissions as well as real GDP. It is interesting to see that the combination of energy efficiency improvement and carbon pricing or LEDS could lead to a substantial reduction of CO2 emission, even with positive impacts on economic growth. The energy efficiency improvement, if combined with carbon pricing, promise much bigger emission reduction with much higher GDP growth, than if combined with LEDS.

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Figure 4. Impacts on real GDP and CO2 emissions (% change from BAU, 2018~2050)



	BAU	Ctax	CtaxLed	Led	LedEff	CtaxEff	Eff	CtLeEf
RGDP(rs)		-2.05%	-5.35%	-2.13%	2.71%	9.43%	13.87%	-1.03%
TotalCO2(rs)		-56.00%	-60.43%	-25.78%	-20.54%	-47.02%	34.03%	-58.84%

Regional impacts are quite diverse in real GDP. In the case of carbon pricing, Korea and Japan gain in GDP while all the other regions lose. In the case of LEDS, Japan, LAM and OECD gain while all the other regions lose. The energy efficiency improvement scenario provides GDP gains to all the regions, with India being the biggest beneficiary, followed by REF.

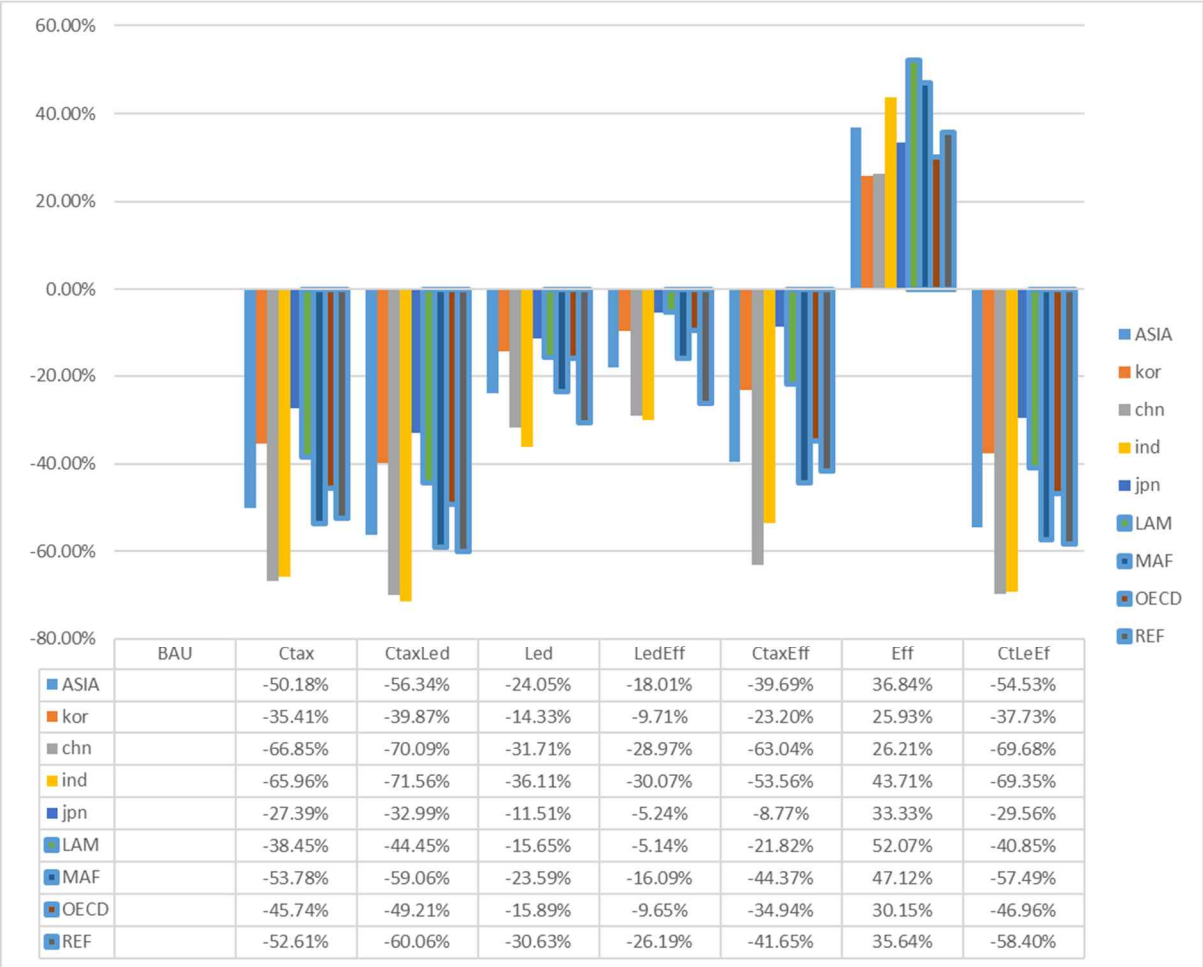
Figure 5. Regional real GDP impacts by scenarios (% change from BAU, 2018~2050)



	BAU	Ctax	CtaxLed	Led	LedEff	CtaxEff	Eff	CtLeEf
ASIA		-0.72%	-9.57%	-6.77%	-1.07%	12.58%	14.95%	-4.38%
kor		0.72%	-2.93%	-2.32%	3.75%	15.39%	15.78%	2.83%
chn		-3.96%	-15.51%	-9.63%	-4.63%	7.42%	14.77%	-11.25%
ind		-4.28%	-16.07%	-10.11%	0.24%	26.30%	38.29%	-7.15%
jpn		0.18%	2.98%	3.55%	8.69%	11.83%	12.58%	7.89%
LAM		-1.03%	-1.87%	0.29%	5.02%	9.02%	11.92%	2.35%
MAF		-3.71%	-12.46%	-7.36%	-1.88%	7.78%	15.81%	-8.03%
OECD		-0.98%	1.56%	3.33%	7.06%	7.56%	9.63%	5.06%
REF		-7.02%	-21.33%	-14.60%	-7.38%	14.72%	28.26%	-15.25%

Regional variation of impacts in CO2 emissions is much smaller than in real GDP. The directions of impacts are the same for all the regions in all the scenarios, with modest differences among regions.

Figure 6. Regional CO2 impacts by scenarios (% change from BAU, 2018~2050)

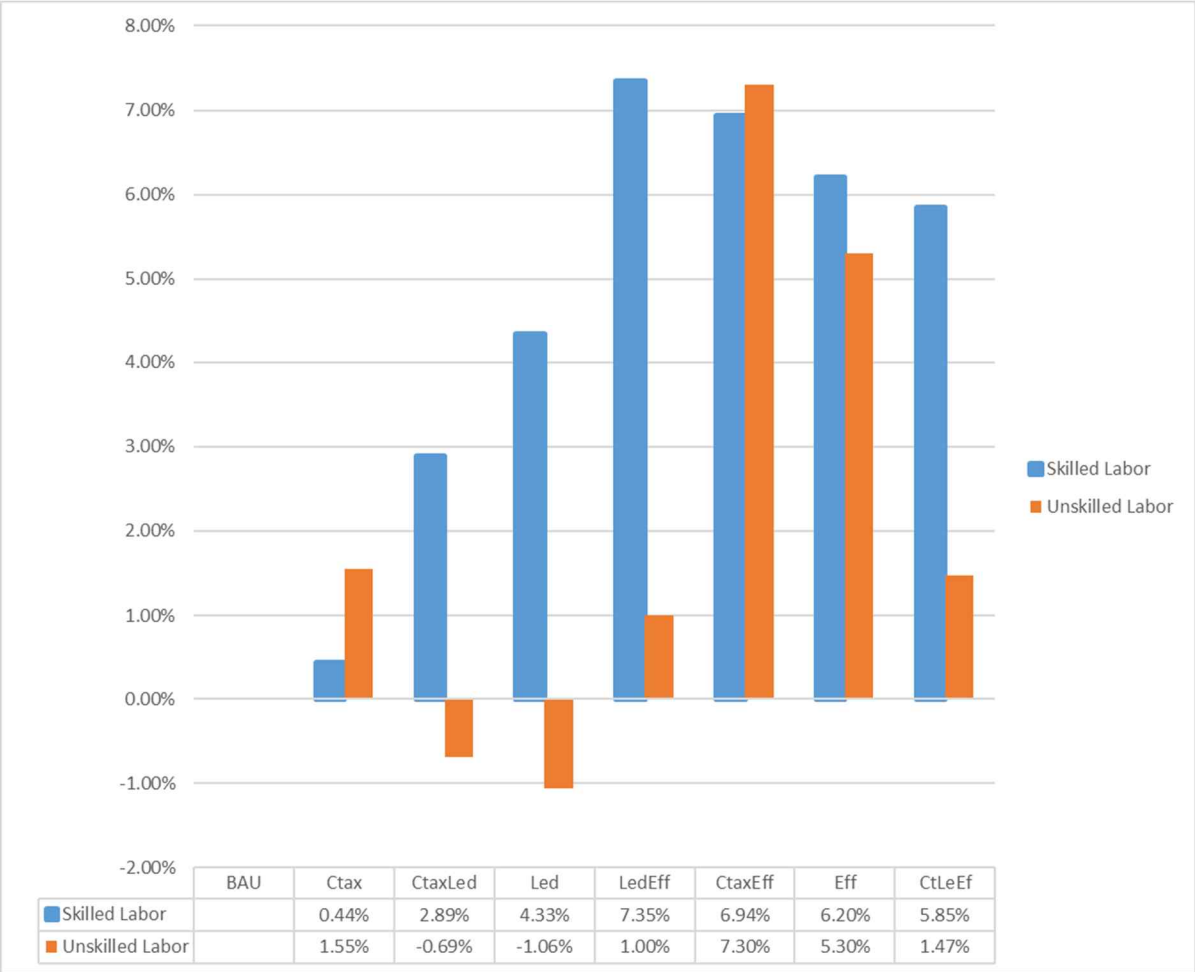


	BAU	Ctax	CtaxLed	Led	LedEff	CtaxEff	Eff	CtLeEf
ASIA		-50.18%	-56.34%	-24.05%	-18.01%	-39.69%	36.84%	-54.53%
kor		-35.41%	-39.87%	-14.33%	-9.71%	-23.20%	25.93%	-37.73%
chn		-66.85%	-70.09%	-31.71%	-28.97%	-63.04%	26.21%	-69.68%
ind		-65.96%	-71.56%	-36.11%	-30.07%	-53.56%	43.71%	-69.35%
jpn		-27.39%	-32.99%	-11.51%	-5.24%	-8.77%	33.33%	-29.56%
LAM		-38.45%	-44.45%	-15.65%	-5.14%	-21.82%	52.07%	-40.85%
MAF		-53.78%	-59.06%	-23.59%	-16.09%	-44.37%	47.12%	-57.49%
OECD		-45.74%	-49.21%	-15.89%	-9.65%	-34.94%	30.15%	-46.96%
REF		-52.61%	-60.06%	-30.63%	-26.19%	-41.65%	35.64%	-58.40%

The labor market effects are mostly positive. Impacts on unskilled labor in ‘Led’ and ‘CtaxLed’ are negative with all the others positive. The energy efficiency improvement with carbon pricing (‘CtaxEff’) provides a significant increase in the market supply in both the skilled and unskilled labor. The carbon pricing scenario, assumed with tax recycling towards labor tax reduction, shows positive impacts on both the skilled and unskilled labors, while the LEDS scenario shows negative impacts on unskilled labor although its positive impact on skilled labor is quite substantial.

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Figure 7. Impacts on skilled and unskilled labor (% change from BAU, 2018~2050)



	BAU	Ctax	CtaxLed	Led	LedEff	CtaxEff	Eff	CtLeEf
Skilled Labor		0.44%	2.89%	4.33%	7.35%	6.94%	6.20%	5.85%
Unskilled Labor		1.55%	-0.69%	-1.06%	1.00%	7.30%	5.30%	1.47%

2.6 Summary and Policy Implications

This study developed a computable general equilibrium (CGE) model for evaluating low energy demands (LED) scenarios. The CGE model is a global multi-regional recursive dynamic CGE with 9 regions and 13 sectors, utilizing the GTAP 10 database.

We defined a LED scenario in a way that the share of energy consumption is diminishing over time so as to be implementable in a CGE model. We constructed two more scenarios, energy efficiency improvement and carbon pricing, to compare the impacts of LED scenario with. Various combinations among the three scenarios are also investigated to evaluate the interactions between different policy and behavioral changes.

We found that the LED scenario leads to a significant reduction of CO2 emissions but with a negative, although quite small, impacts on real GDP. Carbon pricing scenarios also show significant reductions of CO2 with negative impacts on real GDP, while Energy Efficiency scenario results in huge increase of CO2 emissions as well as real GDP. It is interesting to see that the combination of energy efficiency improvement and carbon pricing or LEDS could lead to a substantial reduction of CO2 emission, even with positive impacts on economic growth. The energy efficiency improvement, if combined with carbon pricing, promise much bigger emission reduction with much higher GDP growth, than if combined with LEDS.

The results show that the energy efficiency improvements tend to increase, rather than decrease, CO2 emissions due to the rebound effect of bigger consumption of energy with higher efficiency, which is accompanied with lower cost of purchases. This provides an important policy implication that the policies to improve energy efficiency in themselves are not effective in reducing CO2 emissions and to avoid such unintended results, we need to apply complementary regulation, such as carbon pricing, to curb climate pollutants. In addition, the combination of energy efficiency and carbon pricing promises substantial CO2 reductions as well as economic growth at the same time.

The LED scenarios are often considered as promising opportunities that guarantee large CO2 reductions with no or little associated costs. The simulations with a CGE model in this study support such possibilities and indicate we have good reason to promote LED society by way of education or campaign. This study also shows that we can attain significant emission reductions with even negative costs if we combine regulatory measures such as carbon pricing with energy efficiency improvements. The mix of policies provides double dividends such that we can improve not only environmental performance but also economic outcome.

3 Understanding of the Characteristics of Residential Electricity Demand in Korea[2] Introduction

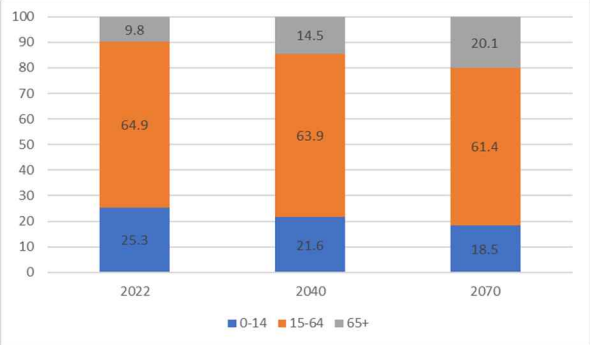
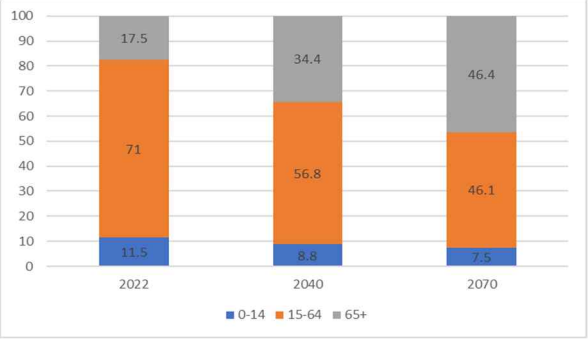
The understanding of the drivers of energy demand becomes more and more important. IPCC (2022) indicates the importance of the demand-side approach in achieving the global 1.5- and 2-degree targets, and the demand-side solutions require an in-depth and broad understanding of social aspects, including human behavior, ideas, and lifestyle. While there is relatively better and more information on the supply-side and technological options, the demand side has not been explored extensively.

While an aging society is a global trend, Korea has been showing an exceptional trend in demographic structure change. Particularly in recent years, Korea has been experiencing a significant and rapid change in demographic and household structure. The country's fertility rate, which indicates the average number of children born to a woman over a lifetime, reached 0.81 in 2021 and was recorded as the world's lowest fertility rate. On the other hand, Korea's life expectancy at birth has increased and was recorded at 83 in 2020, which is much higher than the global average of 72 (World Bank, 2023). The continued low fertility rates and long life expectancy lead to a rapid change in demographic and household structure, and the pace of change is expected to be accelerated in the future. The figure indicates the population prospects estimated in 2022. The share of the aged population over 65 would exceed 30% by 2040 and become almost half of the population by 2070. This trend is quite distinctive compared to the global trend. Globally, the average world share of the aged population would gradually increase and reach 14.5% in 2040 and 20.1% in 2070.

[2] This chapter includes some parts of 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

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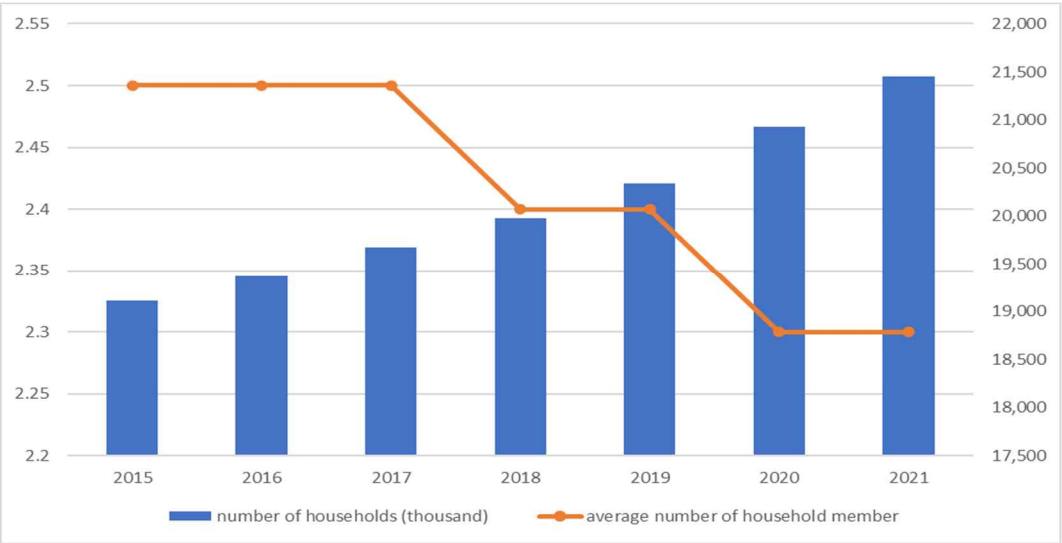
Figure 8.Population Structure (World vs. Korea)

World	Korea
	

Source: Statistics Korea. (2022).

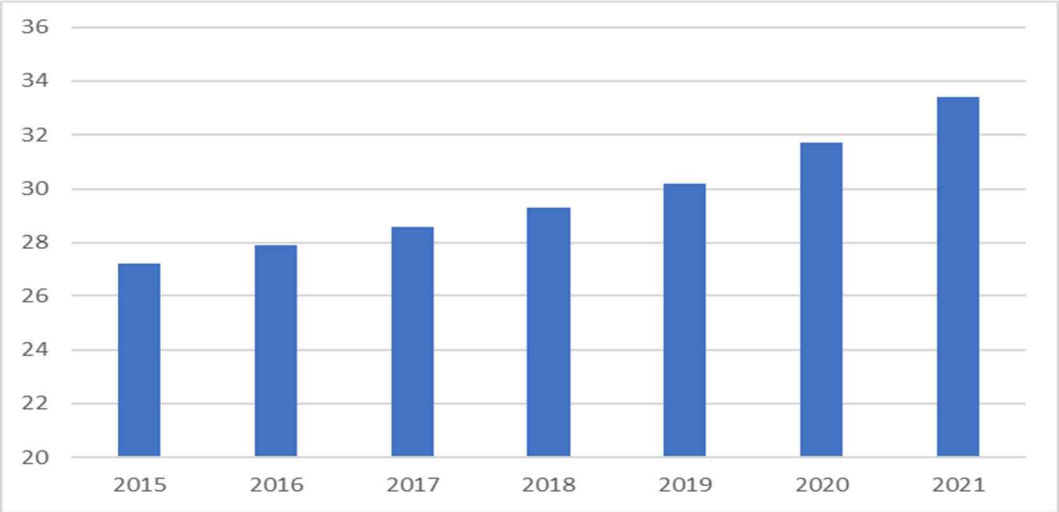
Moreover, the country's household structure is moving towards smaller household sizes and the number of single-person households continues to increase. Particularly, the number of households and the share of the single-person household has been increasing rapidly. In 2015, the total number of households was 19.1 million, and the share of the single-person household was 27.2%. In 2021, the number of the household became 21.4 million, and the share of the single-person household exceeded 33%. Moreover, it showed a clear trend of a gradual increase in the share of two-person households and a decrease in the share of households with three or more persons, and this leads to a decrease in the average number of persons in a household.

Figure 9. Total Number of households (right, thousand) and Average number of household member (left, person)



Source: KOSIS. (2023).

Figure 10. Share of single-person household (%)



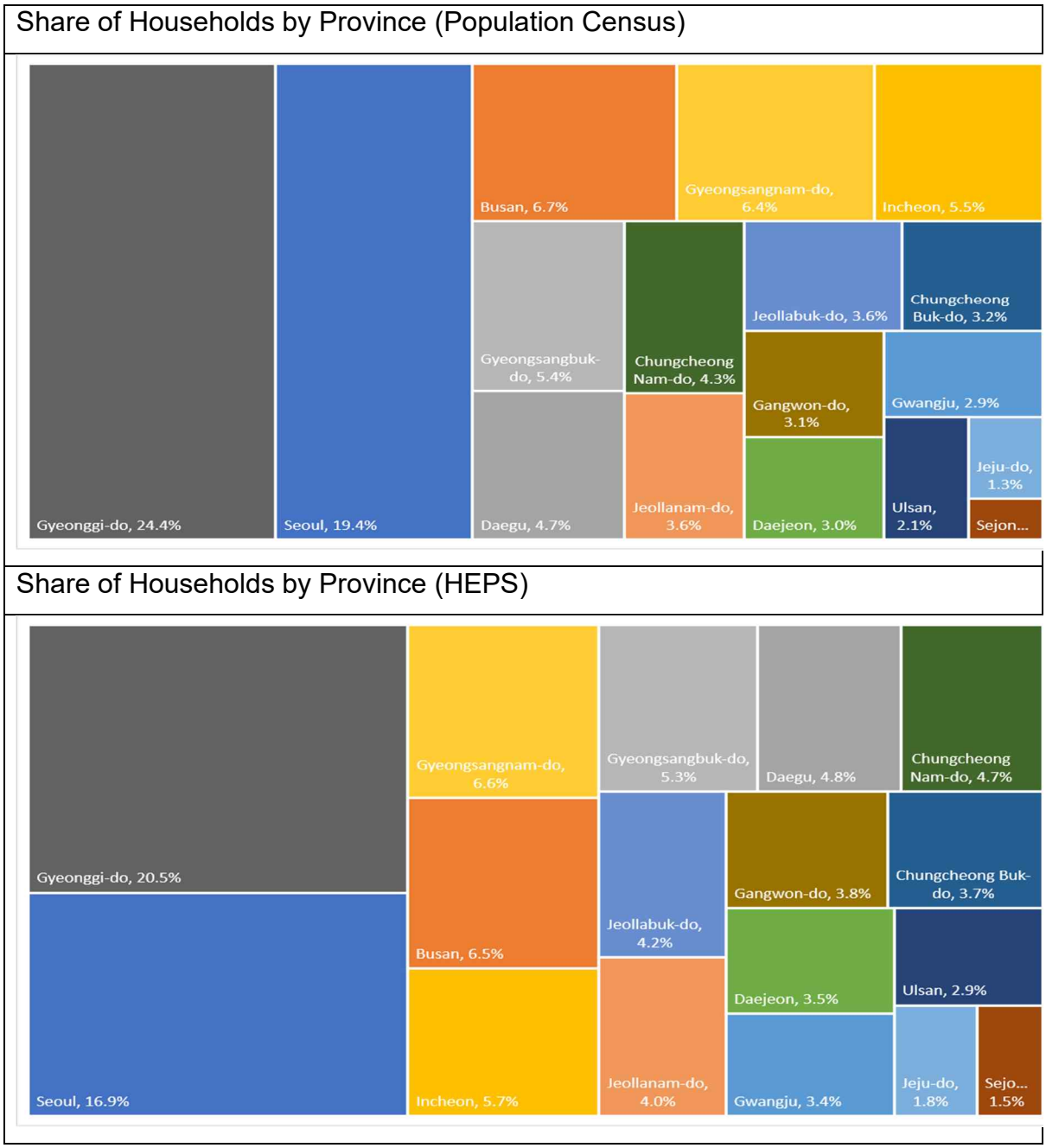
Source: KOSIS. (2023).

3.2 Household Energy Panel Survey

The changes in demographic and household structure inevitably bring changes in human behavior and energy consumption patterns. Also, it would increase the uncertainties in future economic growth and energy demand projections, which are important aspects considered in the national energy and climate policy settings.

This study aims to understand the characteristics of residential electricity consumption by using the updated household panel survey in Korea. Household Energy Panel Survey (hereafter “HEPS”) is a yearly-conducted survey collecting energy consumption and household characteristics of selected households. The study used the latest information on 2019 HEPS results. A distinctive aspect of the 2019 HEPS is the number of households surveyed. In the previous surveys, it targeted 2,520 households in 17 provinces, and its relatively limited number of sample households provided limited information. However, the 2019 HEPS tried to extend its sample to 8,010 households in Korea, and the final survey result included 6,597 households. Also, the composition of the household survey result by province is quite similar to the actual composition of the households in 2019.

Figure 11. Comparison of Share of Households by Province (Population Census vs. HEPS)



However, the survey result includes limited numbers of single-person households. It consists of about 17% of the entire household surveyed, which is relatively lower than the census information. Also, in Seoul and Gyeonggi-do provinces, the shares of the single-person household out of the household surveyed in each province indicated 7.3% and 10.4%, respectively. More than 30% of the surveyed households are two-persons households, and 28.4% of the surveyed households have four or more persons in a

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household.

The distribution of the age of the household head indicates that the household head's age of more than 66% of the surveyed households is in their 50s or older. Particularly, 36.3% of the surveyed household answered that the age of the household head is in the 60s or older. The monthly income of surveyed households is located largely between 200 million KRW and 600 million KRW. The shares of surveyed households with monthly income between 200 million KRW and 400 million KRW and between 400 million KRW and 600 million KRW are 33.4% and 30.7%, respectively.

Regarding housing, the survey result indicates about half of the surveyed households live in an apartment, approximately 32% of the surveyed households live in a detached house, and the rest lives in other types of housing, including multi-family housing. More than 60% of the housing where surveyed households are living was built in the 1990s and 2000s, and the size of the housing of nearly 88% of surveyed households is smaller than 99 m^2.

Also, the survey results provide information on appliance ownership and usage and energy consumption. For heating, over 68% of the surveyed households use city gas as a main fuel, and about 11% of the surveyed households use district heating. Only 5.8% of the surveyed household use electricity as their main fuel for heating. However, the survey indicates a large number of households use supplement heating devices, such as electric pads, and only 34% of the surveyed household answered that they do not use supplement heating devices. This implies while a large number of households mainly depend on gas and oil products for heating, they also use other sources, including electricity, for heating, and it is necessary to identify the ownership and use patterns of heating appliances in analyzing household's electricity demands. Moreover, more than 80% of surveyed households use two types of cooling devices, such as air conditioners and fans.

Despite some limitations, this survey information provides a wide range of information on household characteristics and their energy consumption patterns. The study extracted some key information from the survey results to identify the characteristics of the household's energy consumption. The survey information provides a wide range of information, including housing, cooling/heating, energy consumption, appliance

usage patterns, and household information. Instead of using all the variables provided by the survey, the study selected some key indicators for the analysis.

3.3 Data and Methodology

The survey includes various categorical and numerical variables, and this study identifies some key variables, such as household characteristics, housing, and appliance ownership and usage patterns. For better understanding, this study separates four seasons because Korea typically has four different seasons, so the energy consumption patterns may be different by season. To do so, the monthly electricity consumption is averaged by season: (Spring) March – May, (Summer) June – August, (Fall) September – November, and (Winter) December – February. The common household and housing characteristics are included in all seasons, and ownership and usage of heating and cooling devices are only considered in Winter and Summer, respectively. This study excluded some samples with missing key variables and substantial outliers, so the number of the remaining household samples is 6,557 households. The name and explanations of variables used in each season are given in the following table.

Table 5. Variables used in the Analysis

variable	explanation	Spring	Summer	Fall	WInter
cwgt19_hh	weight (household)	Y	Y	Y	Y
single	single = 1; other = 0	Y	Y	Y	Y
old	old = 1; other = 0	Y	Y	Y	Y
s10_city	Province Code	Y	Y	Y	Y
g_r_s10_101	housing type (1= detached; 2= multi-family; 3= apartment)	Y	Y	Y	Y
s10_102_21	floor level	Y	Y	Y	Y
s10_104	Housing direction (South/South East/South West = 1; other = 0)	Y	Y	Y	Y
g_m_r_s10_105	Construction Year (1= before 1970, 2= 1970s; 3= 1980s; 4= 1990s; 5= 2000s: 6= after)	Y	Y	Y	Y
m2_r_s10_106_10	Size of housing (m2)	Y	Y	Y	Y
s10_107	number of rooms	Y	Y	Y	Y
s10_110	number of windows	Y	Y	Y	Y
s10_201_2000	Installed heating devices (1= nothing; 2= regional/district; 3=	Y	Y	Y	Y

	gas/electricity; 4= renewables; 5= others)				
g_r6_s10_201_300	Main heating fuels (1= briquet, kerosene; 2= city gas; 3= district heating; 4= electricty, 5= others)	Y	Y	Y	Y
r_s10_201_4000	Supplement heating devices (1= nothing; 2= regional/district; 3= kerosene, city gas,etc. 4= electricity; 5= renewable; 6= others)	Y	Y	Y	Y
r_2_s10_gassup_04	no supply of city gas = 1; other = 0	Y	Y	Y	Y
s10_203_10	in-door temperature during Winter (at home)				v
s10_203_20	in-door temperature during Winter (when leave)				Y
s10_204_000	number of cooling devices		Y		
g_s10_204_20	cooling temperature (air conditioner): (0: no; 1: below 20; 2: 20-22; 3: 22-24; 4: 24-26; 5: 26 or above)		Y		
s10_205_100	number of cooking devices	Y	Y	Y	Y
r4_s10_205_200	main cooking fuel (1: electricty; city gas; 3: other; 4: none)	Y	Y	Y	Y
r_s10_206_100	installation of renewable (no = 1; yes = 2)	Y	Y	Y	Y
s10_207_70	decide to install renewables by themselves (yes = 1; no = 2) [awareness]	Y	Y	Y	Y
r3_s10_207_40	Size of solar (W)	Y	Y	Y	Y
r_s10_208_41	Size of solar heat (W)	Y	Y	Y	Y
s10_208_70	use of solar heat	Y	Y	Y	Y
r_s10_209_40	size of geothermal (kw)	Y	Y	Y	Y
s10_209_60	use of geothermal	Y	Y	Y	Y
s10_601	Awareness of appliance energy efficiency labelling	Y	Y	Y	Y
s10_602	Whether checking previous year or month's electricity bill	Y	Y	Y	Y
s10_603	Satisfactory level of cooling		Y		
s10_604	Satisfactory level of heating				Y
s10_607	Registration of energy saving program	Y	Y	Y	Y
s10_803_1	household head's sex: Male = 1; female = 0	Y	Y	Y	Y
g_m2_r_s10_803_3	age of household head: 1: 29 or below; 2 = 30s; 3 = 40s; 4 = 50s; 5= 60s or above)	Y	Y	Y	Y
s10_801	number of household members	Y	Y	Y	Y
s10_803_2	household head's education; 1 = middle-school or less; 2 = high-school graduate; 3 = university graduate; 4 = graduate school	Y	Y	Y	Y

s10_803_4	occupations: 1= full-time; 2 = temporary; 3 = self-employment; 4= others	Y	Y	Y	Y
s10_806_adj	annual income (pre-tax)_adjusted (no missing)	Y	Y	Y	Y
tv_all	monthly TV electricity consumption	Y	Y	Y	Y
wash_all	monthly appliance electricity consumption	Y	Y	Y	Y
air_all	summer-time air conditioner electricity consumption		Y		
fan_all	summer-time fan electricity consumption		Y		
ref_all	monthly appliance electricity consumption	Y	Y	Y	Y
dish_all	monthly appliance electricity consumption	Y	Y	Y	Y
cook_all	monthly appliance electricity consumption	Y	Y	Y	Y
clean_all	monthly appliance electricity consumption	Y	Y	Y	Y
airpuri_all	monthly appliance electricity consumption	Y	Y	Y	Y
home_set	number of digital settop, blue-ray and other video/audio devices	Y	Y	Y	Y
coffee_water	number of coffee and water pruifiers	Y	Y	Y	Y
elec_wave	number of electronic waves and ovens	Y	Y	Y	Y
elec_cook	number of electronic cooking devices	Y	Y	Y	Y
airfri	number of air friers	Y	Y	Y	Y
elec_pot	number of electronic pots	Y	Y	Y	Y
foodwaste	number of foodwaste disposal machine	Y	Y	Y	Y
humid	number of humidifier and dehumidifier	Y	Y	Y	Y
styler	number of cloth styler	Y	Y	Y	Y
printer	number of printer and fax	Y	Y	Y	Y
app11_31	number of electric pad				Y
app11_32	number of electric hotwater pad				Y
app11_33	number of electric stove				Y
app11_34	number of electric heater				Y

The dependent variables are the household's average monthly electricity consumption by season. There are many categorical variables in explanatory variables, and the understanding of features is the main focus of the study, so this study categorized the household's average monthly electricity consumption into four groups. With consideration of the Korean progressive electricity pricing, the range of monthly

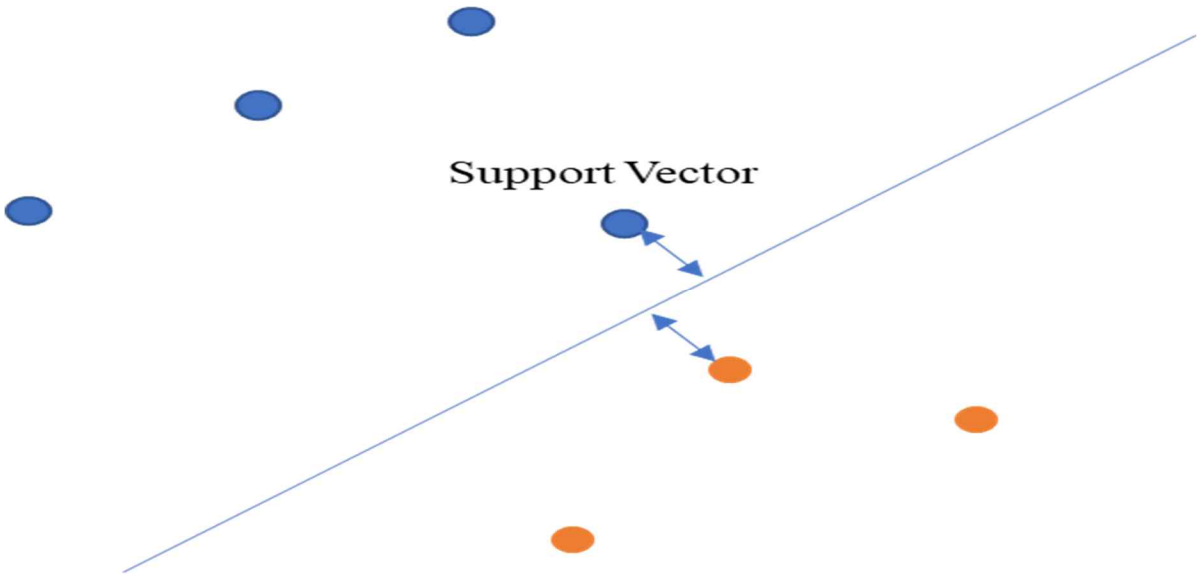
electricity consumption is set as 100kwh. Therefore, the dependent variable categorizes the households into four groups based on the following criteria: (group 1) average monthly electricity consumption below 200 kWh per month; (group 2) 200 kWh ~ 300 kWh; (group 3) 300 kWh ~ 400 kWh; (group 4) above 400 kWh.

Moreover, the study uses household weights provided by the HEPS dataset in sampling. While the survey provides information on 6,500 sampled households, the HEPS dataset provides information on household weights, which indicates how much each surveyed household's characteristics represent the entire Korean household. After excluding the surveyed samples with missing values and substantial outliers, the sum of the weights of all surveyed households is 20,188,466, which is very close to the number of the entire households in Korea.

First, the entire 6,557 household samples are separated into two groups, train and test groups. The ratio of the train and test dataset is 7.5:2.5, and it used a stratified split based on the target variable, which is the monthly average electricity consumption of households by season. After the train-test split, the weights of each observation in the train set are adjusted to make the sum of the weights in the train set equal to one. Then, the study draws 20,000 samples from the train dataset with probability, and the probability of each sample being picked is equal to the individual weight.

This study applies Support Vector Machine, Random Forest, and Decision Tree classifiers to classify the household's electricity consumption by season and identify the key features for the classification.

Figure 12. Support Vector Machine Algorithm



Source: Winters-Hilt and Merat, 2007

Support Vector Machine is one of the widely used supervised machine learning methodologies in classification problems. It separates the dataset with a hyperplane, and the distance between the closest data point and the hyperplane, *the margin*, is used for the classification. The Support Vector is the data point, lying on the margin, and this determines the position of the hyperplane. The objective of the Support Vector Machine classifier is to maximize the margin by minimizing $\|w\|^2$ with a penalty for misclassified data points (Winters-Hilt and Merat 2007).

$$\min_{w,b,\xi} \frac{1}{2}\|w\|^2 + C\sum_{i=1}^{n}\xi_i \quad subject \quad to \quad \xi_i \geq 0, y_i(w^T\phi(x_i) + b) \geq 1 - \xi_i$$

The Scikit-learn library used to conduct the Support Vector Machine classification and 'polynomial', 'radial basis function(rbf)', 'sigmoid', and 'linear' kernels are considered. The Support Vector Machine can do the non-linear classification in higher-dimensional feature space by using these kernel functions. Since this methodology conducts classification based on the distance, the scale of the dataset would affect the classification results significantly. Therefore, the study conducts the standardization of the dataset (Winters-Hilt and Merat, 2007; Menon, 2009; Hsu, C. and Lin, 2016; Murty and Raghava, 2016; Müller and Guido, 2019).

Gaussian Radial Basis Function: $\phi(x_i, x_j) = \exp\left(-\gamma\|x_i - x_j\|^2\right) when\ \gamma > 0$

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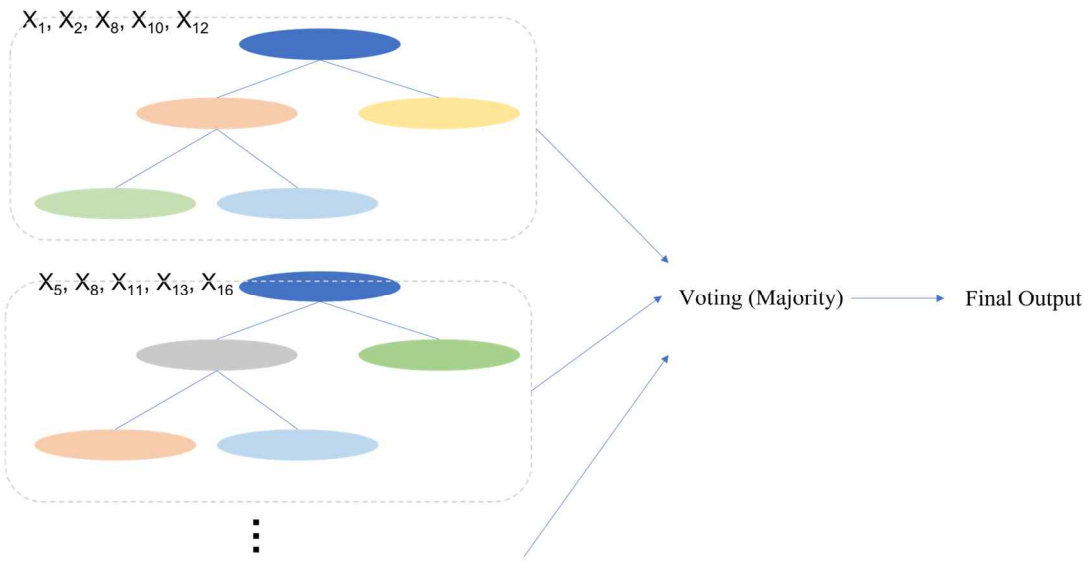
Sigmoid: $\phi(x_i, x_j) = \tanh(-\gamma {x_i}^T x_j + \theta), \gamma > 0$

Polynomial: $\phi(x_i, x_j) = (-\gamma {x_i}^T x_j + \theta)^d, \gamma > 0$

Among different types of standardization methods, the study uses *StandardScaler,* which uses a z-score to standardize the dataset. Also, there are categorical and numerical variables in the dataset, so the study uses OneHotEncoder from the sci-kit learn library. By using OneHotEncoding, a categorical variable becomes a binary column for each category and assigns a value of one to the feature.

Random Forest classifier is an algorithm that a large number of decision trees with the subset of the dataset working as an ensemble. A number of trees make their predictions, and the class with the largest number of votes from the trees becomes the prediction. Typically, the split of the trees is based on the Gini Impurity, and this is the probability that randomly chosen data is incorrectly classified. This algorithm has some advantages, such as not requiring a series of assumptions, handling a large dataset, and providing the evaluation of the importance of features in classification.

Figure 13. Random Forest classification



Source: Moon, (2022)

Lastly, decision tree classification is a supervised machine learning algorithm that identifies key features for the classification. The split starts from the root node and

moves to the decision node with multiple branches based on the decision rule, and the leaf nodes are the endpoints and the final output of decisions (Geron 2019; Müller and Guido, 2019).

The study applies all three algorithms and conducts the classification. The evaluation of the classification is made based on the Confusion Matrix. This matrix includes the following four types: True Positive, True Negative, False Positive, and False Negative. ‘True’ means the actual value, and the ‘Positive’ is the predicted one from the model. This model includes multiple classes (4 classes), so Positive would refer the class of interest, and Negative would be all other classes except the class of interest.

The evaluation metrics used in this study are Accuracy, Recall, Precision, and F1 Score. The definition of Accuracy is the proportion of correct predictions out of the total predictions. Recall is the proportion of True Positive out of the correct predictions, which are True Positive and False Negative. Precision is the proportion of True Positive out of the total positive predictions (True Positive and False Positive). F1 Score is the weighted average of Recall and Precision, which would work well for a dataset with not equal distributions of classes.

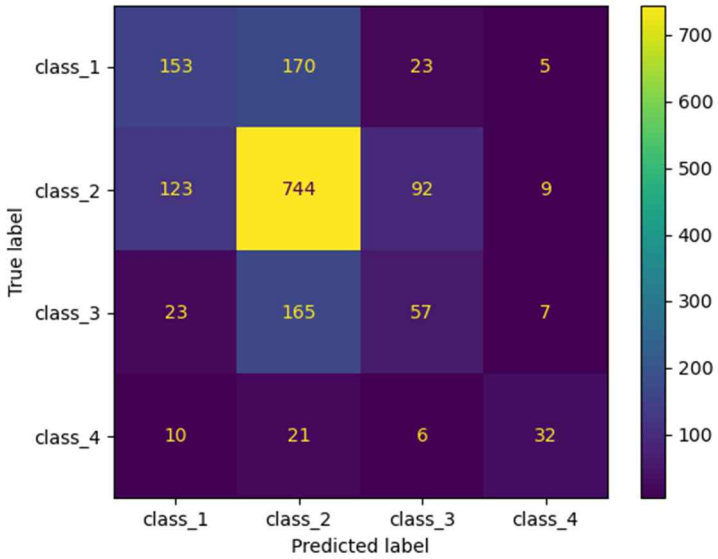
Lastly, it is important to find and tune the hyperparameter for these machine-learning algorithms. The study utilizes RandomizedSearchCV to find the right hyperparameters required for each model. Unlike GridSearchCV, which inputs all combinations of the parameter values, RandomizedSearchCV sets a search space with distributions/ranges of parameter values, and randomly selected parameter values are used and compared. By iterating this process, it tries to find the optimal combination of parameter values. There are some trade-offs. Although this RandomizedSearchCV does not guarantee finding the best combination of parameter values, this can reduce the computation burden and reduce the time necessary to solve the classification problems. This process identifies the best hyperparameters and trains the model with train data, and based on this parameter, the model conducts the classification of the test dataset.

3.4 Results

3.4.1 Spring

First, the study conducts Support Vector Machine to classify the surveyed households' monthly electricity consumption in Spring. The RandomizedSearchCV identifies the best combination of parameters as {'kernel': 'poly', 'Gamma': 0.1, 'C': 100}. The confusion matrix of the Support Vector Machine is as follows:

Figure 14. Confusion Matrix (Support Vector Machine, Spring)



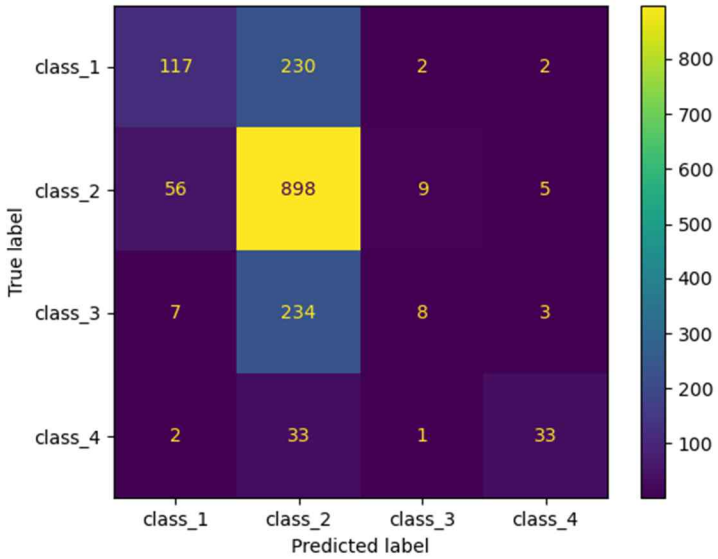
Class 2, households consuming 200 kWh ~ 300 kWh per month, is the typical household, so the model predicts a large portion of households as Class 2. Accuracy is 0.60, and the weighted average of F1 Score is 0.59. The result indicates that the model identifies relatively well on households consuming less than 300 kWh per month, but it finds challenges in identifying the households with larger monthly electricity consumption, particularly between 300kwh – 400 kWh per month.

	precision	recall	f1-score	support
1	0.50	0.44	0.46	351
2	0.68	0.77	0.72	968
3	0.32	0.23	0.27	252
4	0.60	0.46	0.52	69

accuracy			0.60	1640
macro avg	0.52	0.47	0.49	1640
weighted avg	0.58	0.60	0.59	1640

Next, the study uses a Random Forest classifier to train the model with the same train dataset and test the classification with the test dataset. The RandomizedSearchCV identifies the best hyperparameters as {'n_estimators': 216, 'min_samples_split': 4, 'min_samples_leaf': 1, 'max_features': 'sqrt', 'max_depth': 50}. The classification result of the test dataset with the Random Forest Classifier is as follows:

Figure 15. Confusion Matrix (Random Forest, Spring)



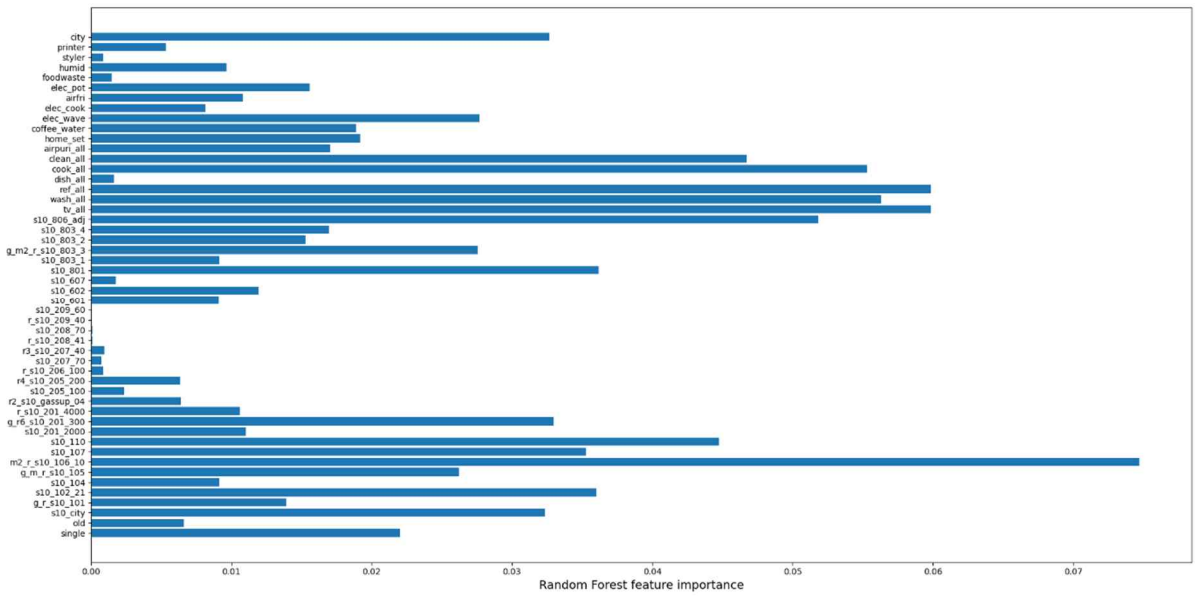
The indicators for model evaluation become slightly better compared to the Support Vector Machine. All classes, except Class 3, the prediction performance becomes slightly improved, and Accuracy and weighted average of F1-score are 0.64 and 0.58, respectively. However, this shows weak performance in classifying Class 3.

	precision	recall	f1-score	support
1	0.64	0.33	0.44	351
2	0.64	0.93	0.76	968
3	0.40	0.03	0.06	252
4	0.77	0.48	0.59	69
accuracy			0.64	1640

macro avg	0.61	0.44	0.46	1640
weighted avg	0.61	0.64	0.58	1640

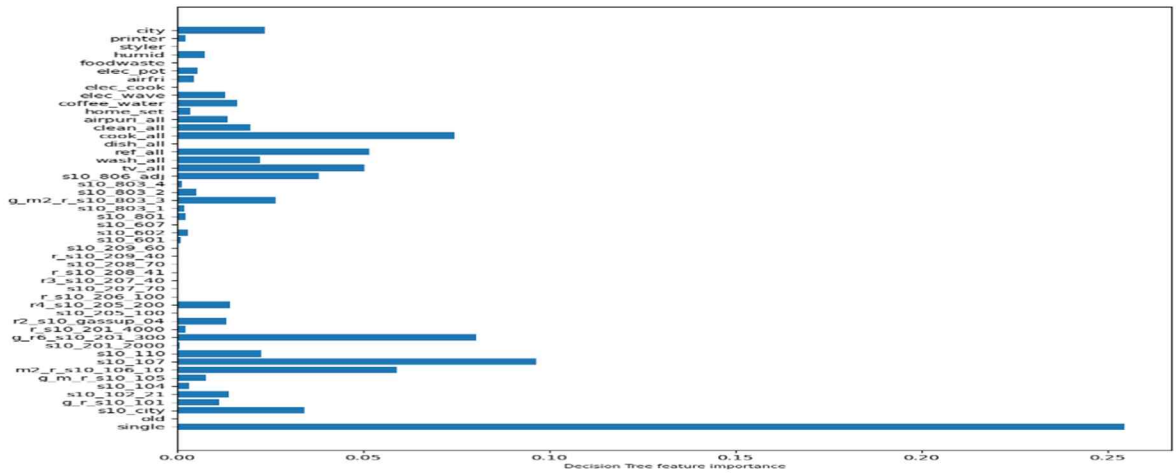
The following figure is the feature importance of the Random Forest model. It identifies 'm2_r_s10_106_10' variable, which is the size of housing (m^2), as the most important feature. Then, the electricity consumption of major appliances, such as refrigerators, tv, and washing machine, and households' income levels are identified as key features for classification. Housing characteristics, such as 'City', floor level and the number of rooms, and the number of household members, are identified as the next important features.

Figure 16. Feature Importance (Random Forest, Spring)



Lastly, Decision Tree classification is conducted on the dataset. RandomizedSearchCV finds the hyperparameter as {max_depth=8, min_samples_split=4}. Decision Tree Classification identifies the 'Single' Dummy as the most important feature for classification and housing size as the next important feature.

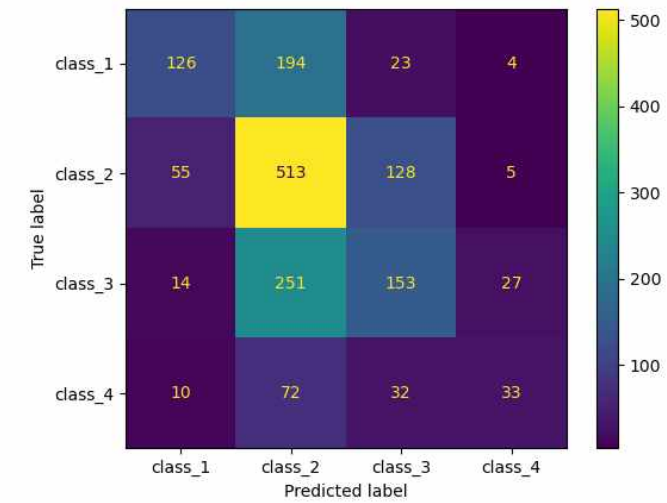
Figure 17. Feature Importance (Decision Tree, Spring)



3.4.2 Summer

Similar to the Spring case, the study conducts Support Vector Machine classification to classify the monthly electricity consumption of the surveyed households in Summer. The RandomizedSearchCV identifies the best combination of parameters as {'kernel': 'rbf', 'gamma': 0.1, 'C': 100}. The confusion matrix of the Support Vector Machine is as follows:

Figure 18. Confusion Matrix (Support Vector Machine, Summer)



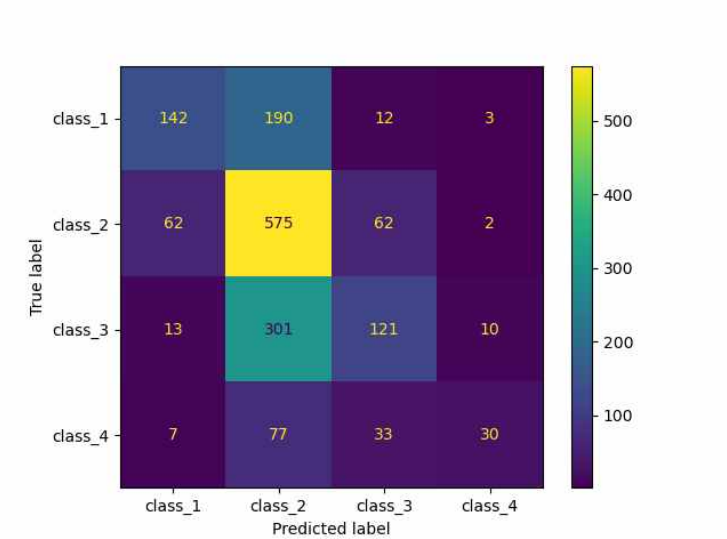
Similar to the previous case, the model predicts a large portion of observations in the test dataset as Class 2. The following result is the evaluation of the classification. The accuracy and the weighted average of F1 Score are 0.50 and 0.48, respectively. Compared to the Spring case, it provides somewhat better performance in classifying

Class 3 but less performance in classifying Class 4.

	precision	recall	f1-score	support
1	0.61	0.36	0.46	347
2	0.50	0.73	0.59	701
3	0.46	0.34	0.39	445
4	0.48	0.22	0.31	147
accuracy			0.50	1640
macro avg	0.51	0.42	0.44	1640
weighted avg	0.51	0.50	0.48	1640

The Random Forest classification is conducted to the same train and test dataset. The RandomizedSearchCV finds the best hyperparameter as {'n_estimators': 242, 'min_samples_split': 6, 'min_samples_leaf': 1, 'max_features': 'sqrt', 'max_depth': 48}. Also, the following information and confusion matrix shows the performance of the classification of Random Forest Classification.

Figure 19. Confusion Matrix (Random Forest, Summer)



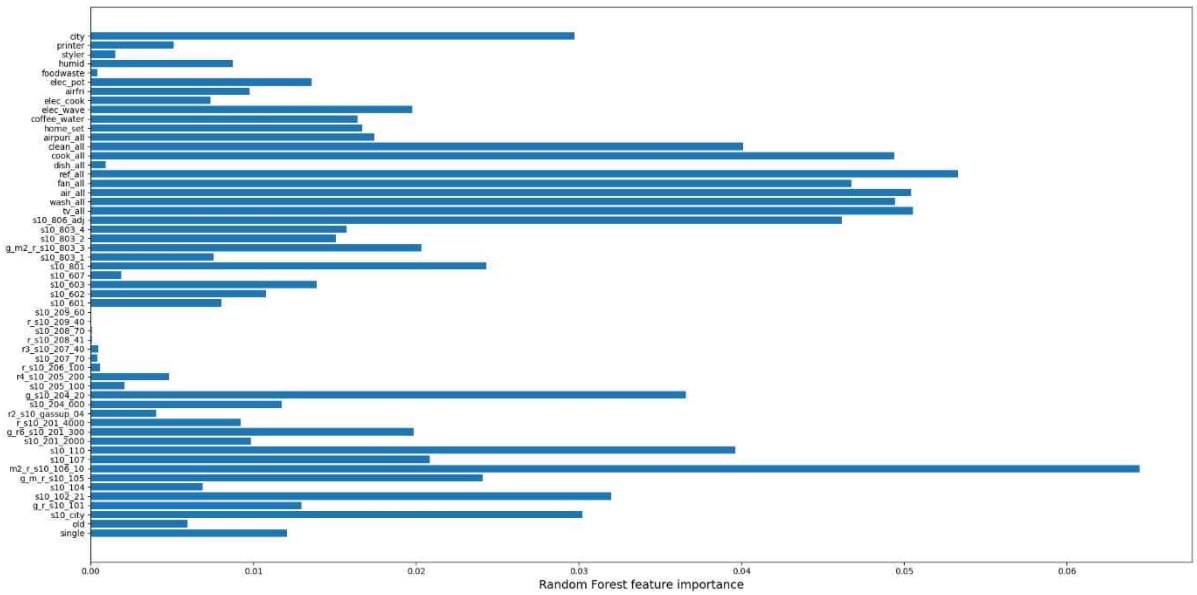
	precision	recall	f1-score	support
1	0.63	0.41	0.50	347
2	0.50	0.82	0.62	701
3	0.53	0.27	0.36	445
4	0.67	0.20	0.31	147
accuracy			0.53	1640

macro avg	0.58	0.43	0.45	1640
weighted avg	0.55	0.53	0.50	1640

Compared to the Support Vector Machine, it indicates better performance in terms of Accuracy and weighted average of F1 Score, which are 0.53 and 0.50, respectively. Still, a large proportion of the test dataset is classified as Class 2.

The following figure shows the feature importance of Random Forest Classification. It shows that ‘m2_r_s10_106_10’ (size of housing) is the most significant feature for classification. The electricity consumption of key appliances, including air conditioners, tv, and washing machines, are also very important features for classification. From the household’s characteristics, the annual income, occupations, and cooling temperature setting in Summer are also identified as important features. However, the number of household members and dummy variables, such as old and single, shows relatively less importance.

Figure 20. Feature Importance (Randdom Forest, Summer)

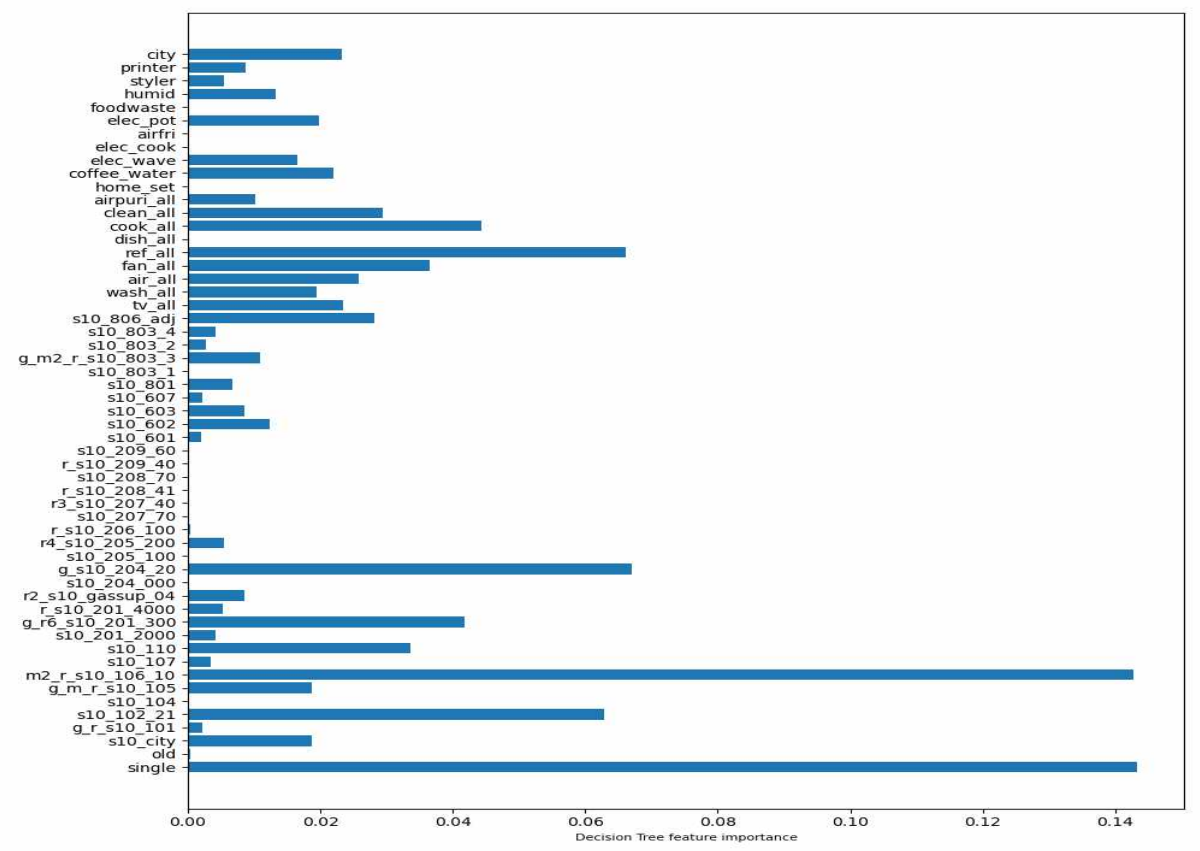


This is household-level electricity consumption, so it may not distinctively show the feature importance of single-person households or households with elderly people.

Next, the Decision Tree classification is conducted. RandomizedSearchCV finds the best hyperparameters as {max_depth=9, min_samples_split=3}.

The following figure shows the feature importance of Decision Tree classification. Interestingly, this result shows ‘Single’ dummy and the size of the housing are the key feature for classification, followed by the cooling temperature setting, floor level, and electricity consumption of the refrigerator. This shows the importance of single-person households in understanding household electricity consumption, and housing and characteristics, such as the size of housing, and floor level, as well as behavioral characteristics, such as cooling temperature setting, are also important features in a household’s monthly electricity consumption in Summer.

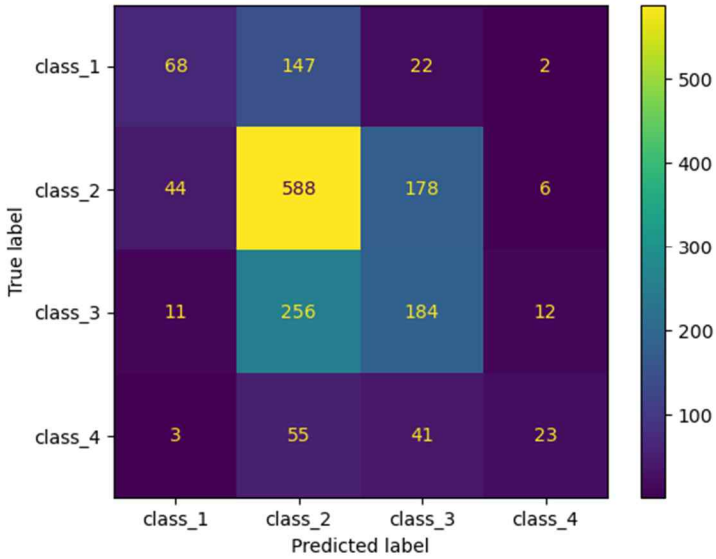
Figure 21. Feature Importance (Decision Tree, Summer)



3.4.3 Fall

The study applies three machine learning algorithms to the monthly electricity consumption in Fall. The study uses the same variables as Spring for analysis. RandomizedSearchCV finds the best hyperparameters of Support Vector Machine classifier as {'kernel': ‘rbf', 'gamma': 0.1, 'C': 10}. The confusion matrix is shown as follows:

Figure 22. Confusion Matrix (Support Vector Machine, Fall)

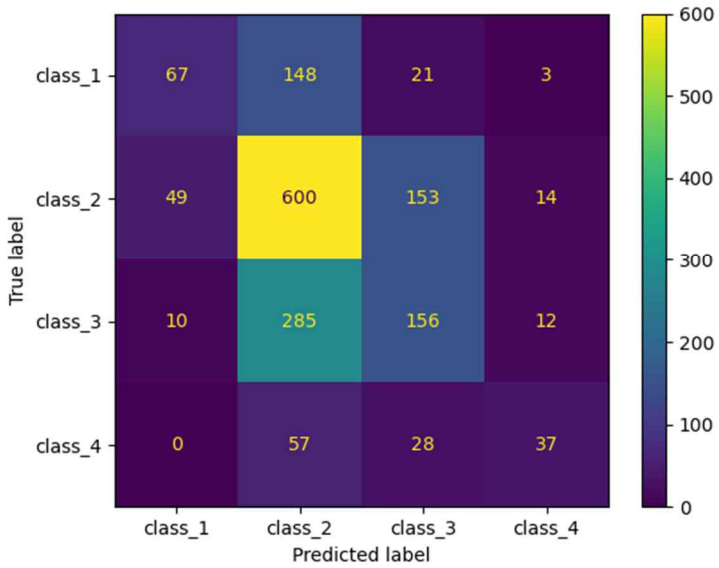


The evaluation metrics show that Accuracy and the weighted average of F1 Score are 0.53 and 0.51, respectively, and it shows similar statistics as the other seasons. This model also shows that the precision score is relatively low in classifying Class 3.

	precision	recall	f1-score	support
1	0.54	0.28	0.37	239
2	0.56	0.72	0.63	816
3	0.43	0.40	0.41	463
4	0.53	0.19	0.28	122
accuracy			0.53	1640
macro avg	0.52	0.40	0.42	1640
weighted avg	0.52	0.53	0.51	1640

For the Random Forest classification, the RandomizedSearchCV find the hyperparatmers as {'n_estimators': 242, 'min_samples_split': 6, 'min_samples_leaf': 1, 'max_features': None, 'max_depth': 33}. The Confusion Matrix and the evaluation metrics are as follows:

Figure 23. Confusion Matrix (Random Forest, Fall)

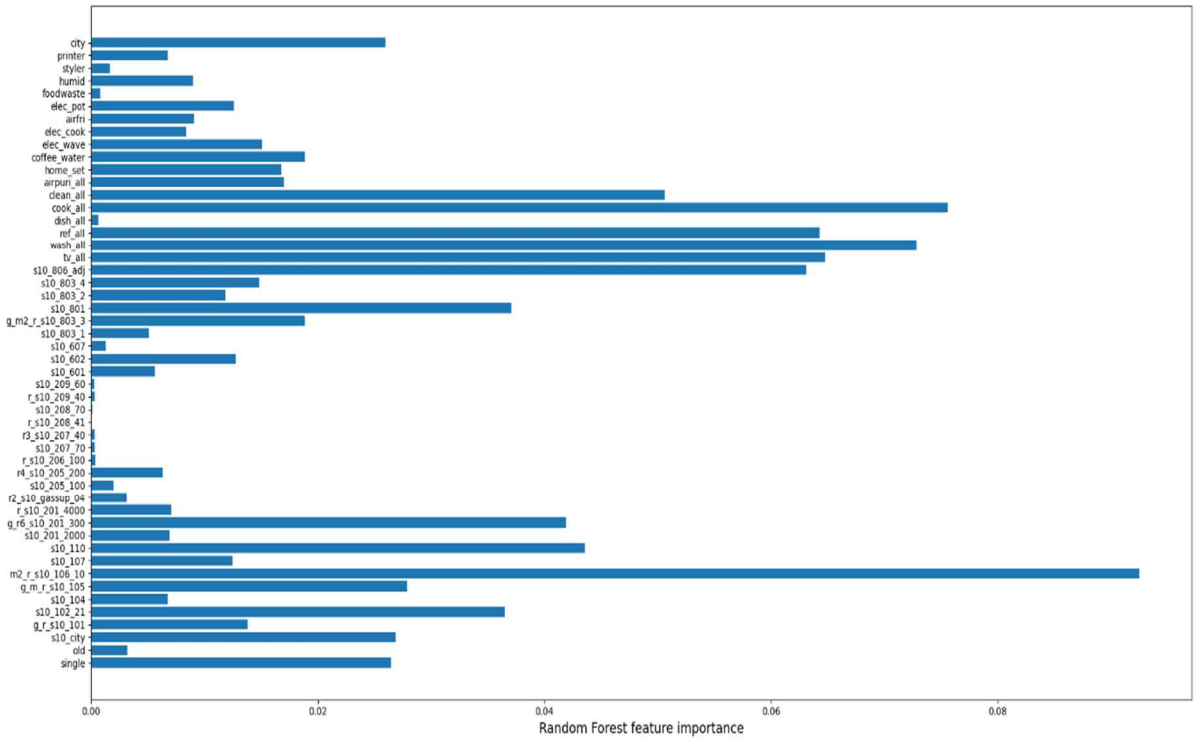


	precision	recall	f1-score	support
1	0.53	0.28	0.37	239
2	0.55	0.74	0.63	816
3	0.44	0.34	0.38	463
4	0.56	0.30	0.39	122
accuracy			0.52	1640
macro avg	0.52	0.41	0.44	1640
weighted avg	0.52	0.52	0.50	1640

In the other cases, Random Forest Model provides a better result compared to Support Vector Machine, but in Fall, the classification results of the two models are quite similar, but in terms of Accuracy and the weighted average of F1 Score, Support Vector Machine indicates a slightly better result than Random Forest Classification.

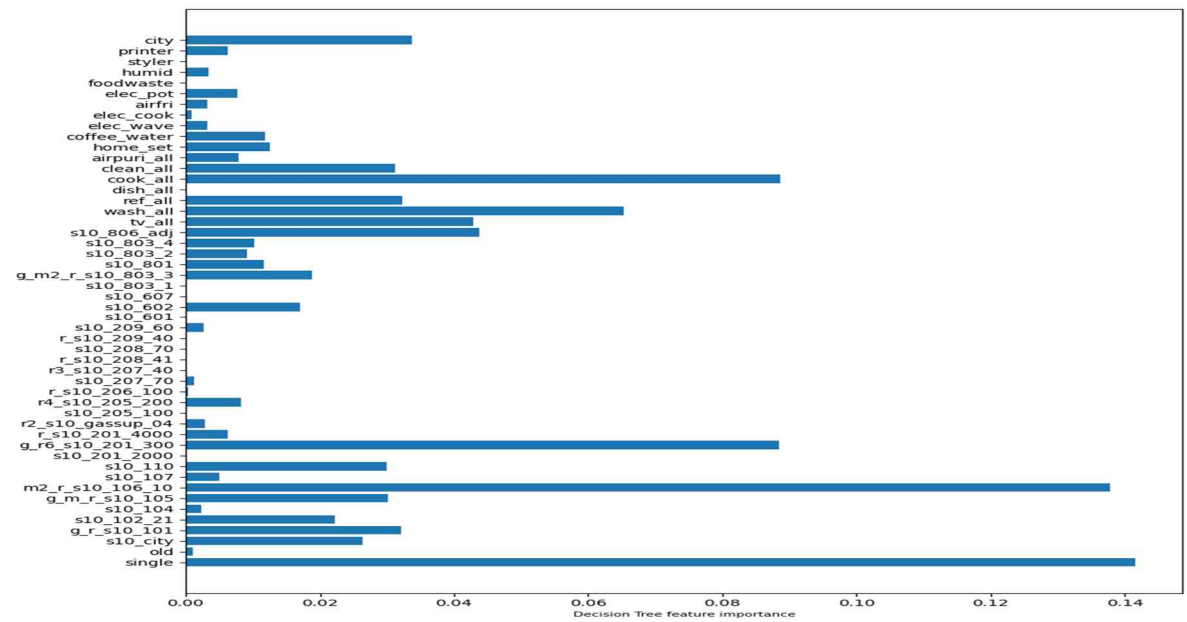
The feature importance figure indicates a very similar result to the previous seasons. It also identifies the housing size as the most important feature, and the use of appliances, income level, main heating fuels, and the number of household members are also important, relative to the other features.

Figure 24. Feature Importance (Random Forest, Fall)



Next, the study conducts Decision Tree Classification and compares its feature importance with Random Forest Classification. Interestingly, this model finds the Single dummy as the most important feature, and the housing size is the next important feature. Similarly, the electricity use of appliances, main heating fuels, and income level are also considered important features.

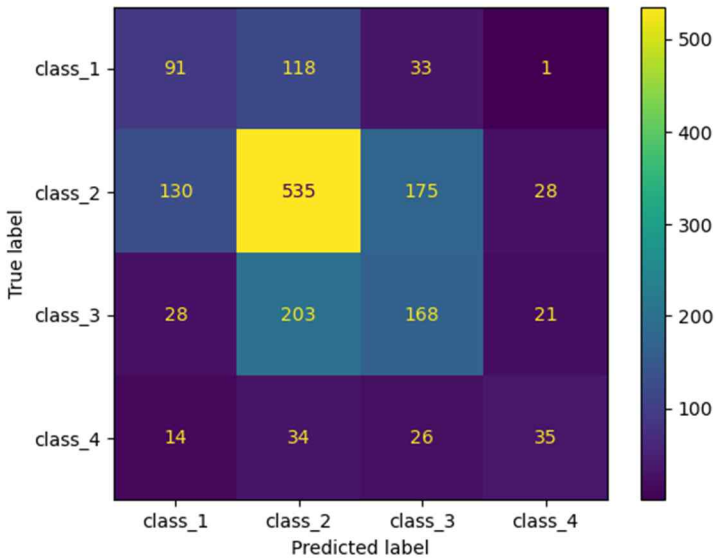
Figure 25. Feature Importance (Decision Tree, Fall)



3.4.4 Winter

Lastly, the study applies three machine learning algorithms to the monthly electricity consumption in Winter. RandomizedSearchCV finds the best hyperparameters of Support Vector Machine classifier as {'kernel': 'poly', 'gamma': 1, 'C': 10}. The confusion matrix is shown as follows:

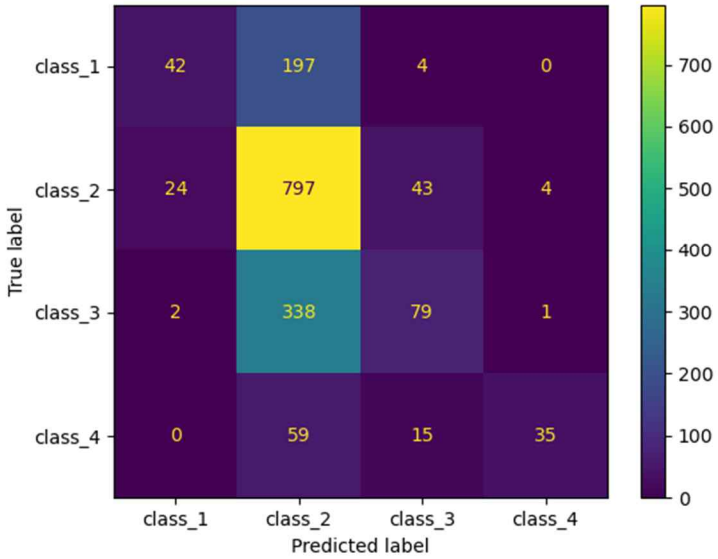
Figure 26. Confusion Matrix (Support Vector Machine, Winter)



The evaluation metrics indicate Accuracy and the weighted average of F1 Score are 0.51 and 0.50, respectively.

Also, the study conducts Random Forest classification. Similar to other cases, Random Forest classification performs slightly better than Support Vector Machine. RandomizedSearchCV finds the best hyperparameters for Random Forest Classification as {'n_estimators': 422, 'min_samples_split': 6, 'min_samples_leaf': 1, 'max_features': 'log2', 'max_depth': 21}. With these hyperparameters it classifies the test dataset. The Confusion matrix and the evaluation of classification performance are as follows:

Figure 27. Confusion Matrix (Random Forest, Winter)



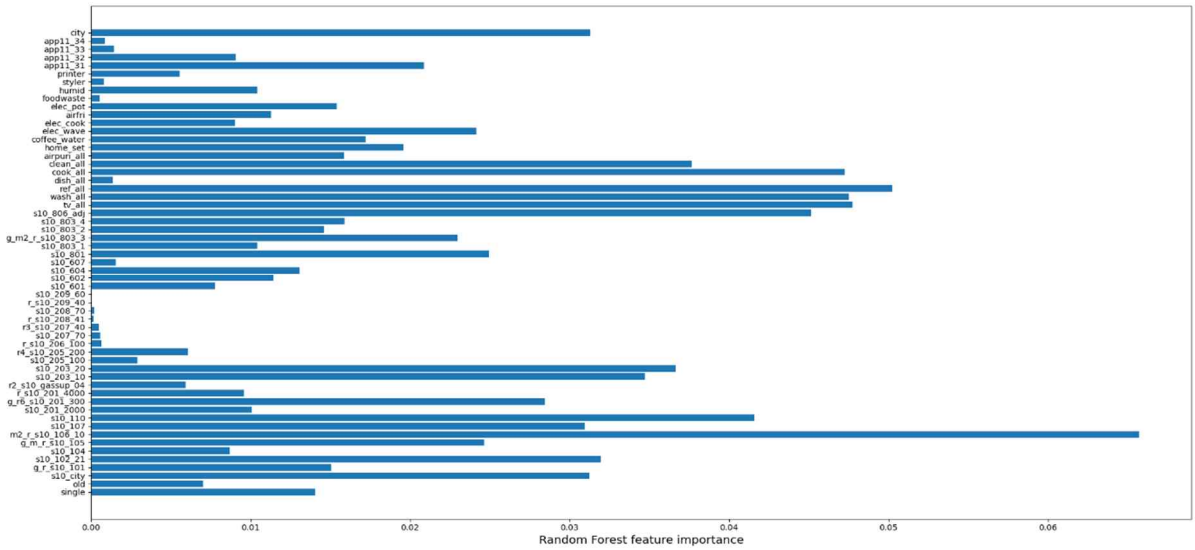
	precision	recall	f1-score	support
1	0.62	0.17	0.27	243
2	0.57	0.92	0.71	868
3	0.56	0.19	0.28	420
4	0.88	0.32	0.47	109
accuracy			0.58	1640
macro avg	0.66	0.40	0.43	1640
weighted avg	0.60	0.58	0.52	1640

As mentioned, Accuracy and weighted average F1 Score are 0.58 and 0.52, respectively, and these are slightly above those metrics of Support Vector Machine. Also, it provides relatively good precision with above 0.5 in all classes.

The feature importance shows similar results to the other seasons. It shows the size of housing as the most important feature for classification, and the use of appliances and annual income are also considered important features.

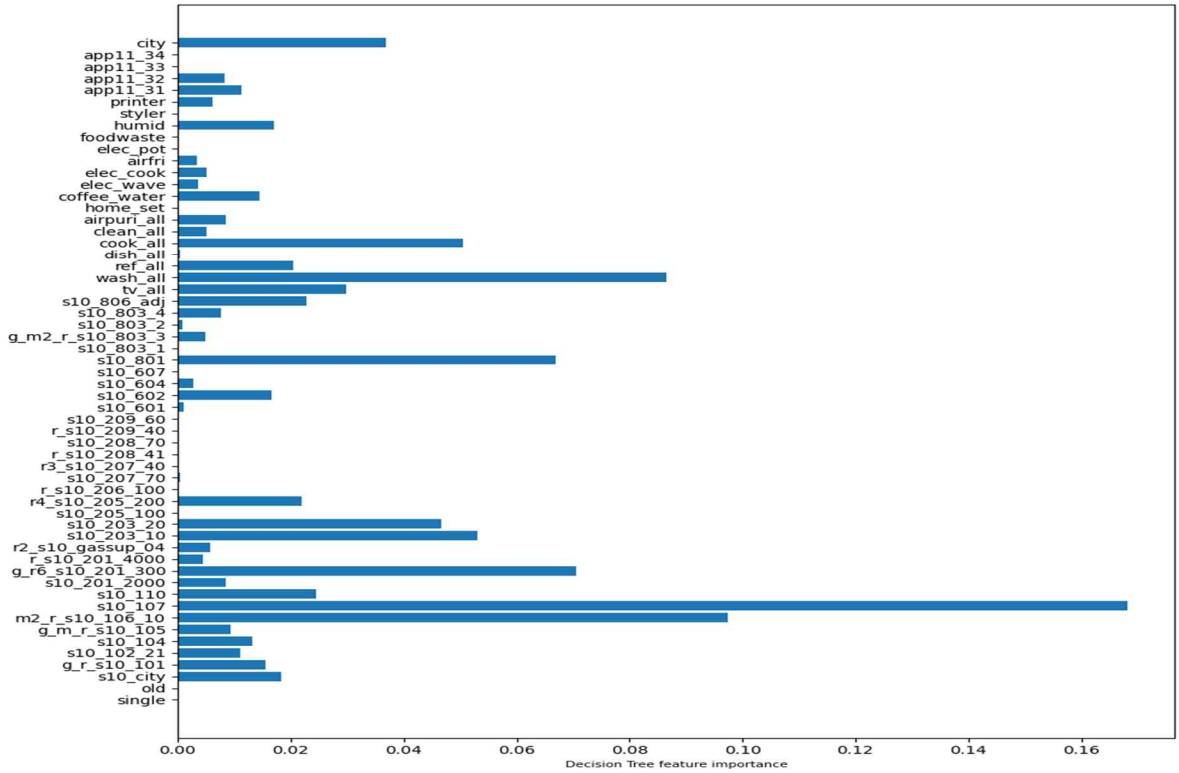
⑦ Korean Society of Climate Change Research

Figure 28. Feature Importance (Random Forest, Winter)



Lastly, Decision Tree Classification is conducted, and the selected hyperparameter is (max_depth=9). This shows a somewhat different picture from Random Forest Classification. The number of rooms is the most significant key feature in this classification, and the housing size, and the main heating fuel, the number of household members are considered important features. This indicates that housing characteristics and the number of households are important features for classifying households' electricity consumption in the Winter season.

Figure 29. Feature Importance (Decision Tree, Winter)



3.5 Conclusion and Implication

The study utilizes the detailed household survey, the 2019 Household Energy Panel Survey (HEPS), which surveyed the household characteristics, appliance ownership and use, and energy consumption patterns and analyzes the drivers of the household's electricity consumption. This would be an important step for forecasting future household electricity consumption. By understanding the drivers of the electricity consumption and the behavior of the households, the energy demand scenarios can be established in further study. The dataset provides a large number of variables, so the study selects household and housing characteristics and appliance ownership and usage variables. Also, Korea has four distinct seasons, so the study separates four seasons, finds and classifies the monthly average electricity consumption, and selects variables for analysis. Moreover, the study applies three machine learning algorithms, which are Support Vector Machine, Random Forest, and Decision Tree classifications. The study compares the classification performance of Support Vector Machine and Random Forest and also analyzes the feature importances of Random Forest and Decision Tree classifications.

The results indicate that the classification performance of Random Forest classification is relatively better than that of Support Vector Machine. However, the classification performances of the models are not significantly high. There could be some possible explanations that the study considers the household's electricity consumption as a whole, and the household's monthly electricity consumption in a group contains a wide range of households. Also, a large number of households are consuming their electricity between 200 kWh ~ 400 kWh (in the case of Summer, 250 ~ 450 kWh). So, its classification performance might become less significant. If the per capita electricity consumption is additionally considered, it may show the household's characteristics more important. In general, all households own similar sets of appliances and heating/cooling systems, though different sizes and types, so the electricity consumption of a single-person household might not be significantly different from that of other types of households. The Decision Tree classification identifies the 'Single' household dummy as the most important feature, and this indicates the trend of single-person households would be important for the future energy demands of Korea.

However, the feature importance shows some information that the housing characteristics and appliance ownership and usage patterns are very important for understanding the household's electricity consumption. Particularly, the housing size is considered as the most important feature in all scenarios. This characteristic may be closely related to other features because the housing size would affect the needs for cooling and heating demands and the size of the appliances. From this result, it implies that the setting of the future energy demand scenario would be necessary to consider the projections of the number of households, household characteristics, and housing size. Also, the importance of appliance ownership and usage information is necessary to be highlighted as it is related to the household and people's behavior, and the low energy demand scenarios and the future energy demand projections would be largely dependent on human behavior. In further studies, these behavioral characteristics would be further investigated.

References

Aguiar, A., M. Chepeliev, E. L. Corong, R. McDougall, and D. Van Der Mensbrugghe. 2019. The GTAP data base: version 10. Journal of Global Economic Analysis 4(1), 1–27.

Barrett, J., Pye, S., Betts-Davies, S., Broad, O., Price, J., Eyre, N., ... & Scott, K. (2022). Energy demand reduction options for meeting national zero-emission targets in the United Kingdom. Nature Energy, 7(8), 726-735.

Burfisher, M. E. 2016. Introduction to computable general equilibrium models. Cambridge University Press (second edition).

Château, J., R. Dellink, and E. Lanzi. 2014. An overview of the OECD ENV-linkages model: version 3 OECD Environment Working Papers, Issue 65. OECD Publishing. https://www.oecd-ilibrary.org/environment-and-sustainable-development/an-overview-of-the-oecd-env-linkages-model_5jz2qck2b2vd-en.

Corong, E. 2021. GTAP Labor Data Base. Presentation at the 2021 GTAP Advisory Board Meeting, 21 June. https://www.gtap.agecon.purdue.edu/events/Board_Meetings/2021/documents/Presentations/05_LaborDB_EC.pdf.

Edelenbosch, O. Y., Van Vuuren, D. P., Blok, K., Calvin, K., & Fujimori, S. (2020). Mitigating energy demand sector emissions: The integrated modelling perspective. Applied Energy, 261, 114347.

Gaur, A., Balyk, O., Glynn, J., Curtis, J., & Daly, H. (2022). Low energy demand scenario for feasible deep decarbonisation: Whole energy systems modelling for Ireland. Renewable and Sustainable Energy Transition, 2, 100024.

Hsu, C. W., Chang, C. C., & Lin, C. J. (2003). A practical guide to support vector classification.

IPCC .(2022). Climate Change 2022: Mitigation of Climate Change. [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA

Jung, T. Y., Y.-G. Kim, and J. Moon. 2021. The Impact of Demographic Changes on

CO2 Emission Profiles: Cases of East Asian Countries. Sustainability 13(2), 677. https://www.mdpi.com/2071-1050/13/2/677.

K-indicator. (2023). Number of household members. Accessed on https://www.index.go.kr/unify/idx-info.do?idxCd=4229#:~:text=%EC%A0%84%EA%B5%AD%20%EA%B0%80%EA%B5%AC%EC%9D%98%20%ED%8F%89%EA%B7%A0%20%EA%B0%80%EA%B5%AC,%EB%AA%85%EC%9C%BC%EB%A1%9C%20%EA%BE%B8%EC%A4%80%ED%9E%88%20%EA%B0%90%EC%86%8C%ED%95%98%EC%98%80%EB%8B%A4.

KESIS. (2022). 2019 Household Energy Panel Survey. http://www.kesis.net/sub/sub_0001_04.jsp

Koo, Y., Y. Lee, and Y.-g. Kim. 2019. The differentiated impact of emissions trading system based on company size. Climate Policy 19(7), 923–936. https://doi.org/10.1080/14693062.2019.1605329.

KOSIS. (2023). Composition of households, and the number of household members. Accessed on https://kosis.kr/statHtml/statHtml.do?orgId=101&tblId=DT_1JC1516&vw_cd=MT_ZTITLE&list_id=&scrId=&seqNo=&lang_mode=ko&obj_var_id=&itm_id=&conn_path=E1&docId=0337036177&markType=S&itmNm=%EC%A0%84%EA%B5%AD

Menon, A. K. (2009). Large-scale support vector machines: algorithms and theory. Research Exam, University of California, San Diego, 117.

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

Müller, Andreas C, and Sarah Guido. (2019). Introduction to machine learning with Python: a guide for data scientists [translated in Korean]. Translated by Hae Sun Park. Fourth Release ed. Seoul: Hanbit Media. Introduction to Machine Learning with Python.

Murty, M. N., & Raghava, R. (2016). Support vector machines and perceptrons: Learning, optimization, classification, and application to social networks.

Oshiro, K., Fujimori, S., Ochi, Y., & Ehara, T. (2021). Enabling energy system transition toward decarbonization in Japan through energy service demand reduction. Energy, 227, 120464.

Scott, K., Smith, C. J., Lowe, J. A., & Garcia-Carreras, L. (2022). Demand vs supply-side approaches to mitigation: What final energy demand assumptions are made to meet 1.5 and 2° C targets?. Global Environmental Change, 72, 102448.

Shi, Q., Ren, H., Cai, W., & Gao, J. (2019). How to set the proper level of carbon tax in the context of Chinese construction sector? A CGE analysis. Journal of Cleaner Production, 240, 117955.

Statistics Korea. (2022). Population Status and Prospects of World and Korea. https://www.korea.kr/docViewer/skin/doc.html?fn=196936665&rs=/docViewer/result/2022.09/05/196936665

Van Ruijven, B. J., De Cian, E., & Sue Wing, I. (2019). Amplification of future energy demand growth due to climate change. Nature communications, 10(1), 2762.

Winters-Hilt, S., & Merat, S. (2007, November). SVM clustering. In BMC bioinformatics (Vol. 8, No. 7, pp. 1-12). BioMed Central.

World Bank. (2023). Life expectancy at birth, total(years). Accessed https://data.worldbank.org/indicator/SP.DYN.LE00.IN

Social innovation enablers to unlock a low energy demand future

February 2023

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Abstract

We develop a framework for analyzing Low Energy Demand (LED) innovations and use it to identify the key conditions under which technology interventions can be improved and scaled up over the next three decades to contribute to climate change mitigation. Several studies have argued that the scope for mitigation strategies focused on LED is much larger than previously portrayed and have showed that adopting a wide variety of energy-reducing activities would achieve emissions reductions compatible with a 1.5C temperature target. Yet, how realistic achieving such a scenario might be, or what processes would need to be in place to create a pathway to a LED outcome in mid-century remain overlooked. This study contributes to understanding LED's mitigation potential by outlining narratives of LED innovation in three sectors: industry, transport, and building end-use. Our analysis takes an innovation functions approach and thus assesses social, business model, as well as technological innovations for these examples. These lead us to identify a set of eight social enablers required for unlocking LED technological innovation pathways. A key insight is that the distinct characteristics of LED technology make enabling social innovations crucial for their widespread adoption.

A Comparative Evaluation Of The EDITS Scenarios With Similar Scenarios Produced by Other Major Research Institutions in 2021 & 2022

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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

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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. CURRENT EDITS HIGH WITH LOW SCENARIO[1]

The High-with-Low Scenario Narrative

In this paper we define and enrich the narrative of a scenario that shows a world moving rapidly in the direction of the UN Sustainable Development Goals (SDGs), with a focus on resource use and climate change. Our scenario achieves high levels of human wellbeing that are more equitably distributed globally with drastically reduced energy and material consumption compared to today.

Building off the global low energy demand (LED) scenario by Grubler, Wilson et al. (2018), our scenario paradigm can be summarized as **high** wellbeing with **low** resource use. This '**High-with-Low**' juxtaposition reflects a central tenet of sustainable development: achieving high levels of human development while also preserving the natural environment by keeping the human resource use footprint within planetary boundaries (Rockstrom, Steffen et al. 2009).

Sustainable development

Our interpretation of **sustainable development** broadly follows the framework developed by [MCA, 2016]: "*Sustainable Development aims to provide inclusive wellbeing, while increasing development capital und respecting planetary boundaries."*

The focus on **well-being** recognizes both tangible and intangible constituents that include both

[1] This section draws heavily and quotes freely from the High-with-Low narrative document (Grubler. et al., 2022).

material as well as social dimensions. The social dimensions of well-being comprise both individual dimensions (health, education, opportunity) as well as collective dimensions (community, security) dimensions. The term “inclusive” means wellbeing should be universal, i.e. achieved for all.

By increasing **development capital** we refer to the different forms of capital that are needed to run the economy and society, and which we leave behind for future generations enabling them to meet their own needs (Brundtland and Khalid 1987). Different forms of capital are needed for development: physical and economic capital including infrastructures and economic assets; human and social capital including educated work-forces and functioning social institutions; knowledge and innovation capital, an important resource to pass on to future generations; and natural capital including natural resources, environmental amenities, and ecosystem services.

These different forms of capital are partially substitutable, subject to **planetary boundaries**, including those related to climate and atmosphere, biospheric diversity, and biochemical cycles

(Rockstrom, Steffen et al. 2009). Our interpretation of sustainable development therefore allows for non-renewable resources to be depleted, provided this does not infringe on planetary boundaries. For example, copper extraction for electric and digital infrastructure is doable with if impacts are minimized on freshwater, land, biodiversity, and greenhouse gas emissions, and provided that extractive processes enable a significant build-up of physical, social, or knowledge capital for development, rather than just consumption activities.

Services

‘**Services**’ are another key concept in our High-with-Low scenario narrative. Services refer to the amenities or functionalities like comfort, mobility, or social interactions that constitute well-being rather than the resource or economic inputs like income, energy, or materials needed to provide those services. This is an important distinction to traditional conceptualizations that equate well-being with levels of resource use (GDP or energy use per capita).

Our emphasis on services is important for two reasons. First, it makes explicit that there is no fixed, constant relationship between levels of services delivered and their associated inputs; the relationship can be improved by increasing service efficiency. Second, focusing on services (outputs) instead of physical or monetary inputs opens up thinking on alternative forms of service provision. The service of a comfortable home is a better descriptor for human well-being than the cubic meters of gas used to heat it, especially as the service can be provided alternatively by a building shell with weak thermal integrity and ventilation by leaky doors and windows, or by an efficient, well insulated building shell, and managed ventilation with energy recovery.

Central themes of the High-with-Low scenario

The global LED study that provides the start point for this High-with-Low scenario narrative emphasized five 'mega-trends' shaping development to 2050, and five more specific drivers of

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change for resource-intensive energy and land-use systems (Grubler, Wilson et al. 2018).We extend and enrich this LED scenario by showing the importance of three central themes (decent living, innovation, digitalization) and how they inter-link in synergistic ways to ensure a resource efficient future with high and inclusive wellbeing (Figure 1).

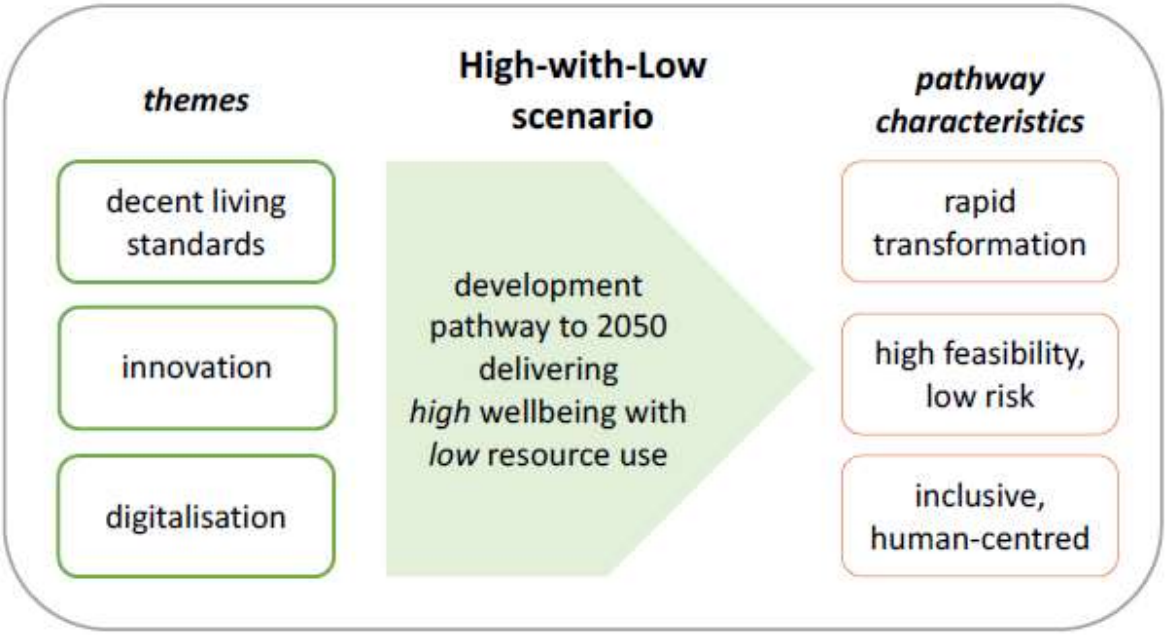


Figure 1. Three Main Themes In The High-With-Low Scenario, And Characteristics Of The Resulting Development Pathway To 2050.

Decent living for all. First and foremost, the High-with-Low scenario is more equitable, fair, and inclusive, with climate and other environmental goals embedded within a broader sustainable and social development agenda. Such a future acknowledges the value of every human being and grants all individuals the right to a **decent life** based on a common and shared responsibility towards other human beings and the planet, both today and into the future. Providing a decent life for all by eliminating all forms of extreme deprivation, under-consumption, and exclusion, has been endorsed globally as desirable on normative grounds including in the targets and goals set by the UN 2030 Agenda (United Nations 2020). Understanding has steadily grown for how poverty eradication enables a larger share of the population to live healthier lives, participate in labor markets, increase productivity, generate employment, improve livelihoods, increase agency and voice, reduce deaths and disability, enhance public acceptability of climate and environmental policies, and become self-reliant (World Bank 2005, Several 2017, Barnes, Samad et al. 2018). The vast global pool of un-served consumers also represent an immense unexploited market (Prahalad, Prahalad et al. 2005). Alleviating

multidimensional poverty and deprivations reduces vulnerability to climate impacts, disasters, and other shocks, as well as the threat of terrorism, conflict and migration (Hallegatte and Rosenberg 2017, Hallegatte, Fay et al. 2018, Bastia and Skeldon 2020).

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Ensuring a decent standard of living for all need not be tied to an ever-expanding set of material consumables that are privately owned. What constitutes a good life, a decent life, a good quality of life, wellbeing, happiness, human flourishing, a life that deprives no one of their ability to meet basic needs and more, have long been debated (Rawls 1971, Doyal and Gough 1991, Max-Neef 1991, Nussbaum 2003, Costanza, Fisher et al. 2007). We follow Rao and Baer (2012) and Rao and Min (2017) in defining **decent living standards (DLS)** as "*a set of universal, irreducible and essential set of material conditions for achieving basic human wellbeing, along with indicators and quantitative thresholds, which can be operationalized for societies based on local customs and preferences*" Table 1. The DLS framework identifies groups of basic need with sub-dimensions for which energy and material prerequisites can be estimated. Physical needs include shelter (housing, indoor comfort), nutrition (food), health and hygiene (water, sanitation, health care). Social needs include socialization (education, social connectedness), mobility (physical connectedness). This is not to imply that non-material needs or intangibles are any less essential to a decent life. Being part of a community, having a say in the shaping of society, feeling and being safe and secure, being able to express identity are also important "protected needs" (Di Giulio and Defila 2019). However, as meeting these needs does not have significant material and resource consequences, they are not the focus of the High-with-Low scenario.
Evidence is growing on opportunities to limit growth of global energy and material demands while meeting decent living standards for all without sacrificing individual wellbeing (Brand-Correa and Steinberger 2017, Haberl, Wiedenhofer et al. 2017). How essential human needs are met also has wellbeing implications that depend on how efficiently resources and materials are used, how service provisioning systems are designed, how social norms and cultures shape use, and whether associated waste and emission streams impact human and planetary health (Figure 2).

Innovation. Innovation is integral to the High-with-Low scenario because limiting warming to 1.5°C while universally providing for human needs within planetary boundaries requires very rapid rates of change. LED technology enabled by digitalization and providing new services amidst changing end user roles has to play a central role (Nemet and Greene 2022). Similarly social and business model innovation, typically in combination with hardware and digital innovation, is central to High-with-Low because: it provides the means for rapid transformation; it encapsulates a dynamic view on LED technology, behavior, and adoption; and it reconciles DLS goals with other aims of the LED scenario. The High-with-Low scenario therefore sees the widespread adoption of existing LED practices, broadening to new geographies and new users, as well as novel combinations of behavior, technology, and business models. All this falls under the rubric of what we mean by **innovation**: improvements and widespread adoption of resource-efficient practices, including hardware, software, and 'orgware' - the institutions and social practices that shape the use of technology.

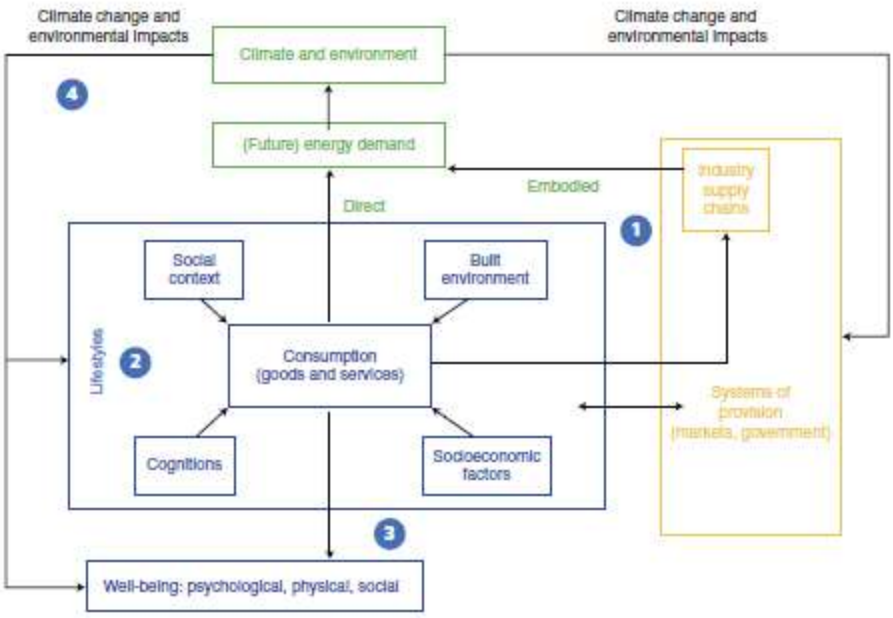


Figure 2. Conceptual Linkages Between Human Well-Being and Climate Change Through Consumption and Its Derived Energy Demand: (1) Energy Demand Modeling and Household Heterogeneity; (2) Lifestyles And Consumption; (3) Consumption And Well-Being; (4) Equity And Well-Being. The Colored Boxes Differentiate Individuals/Households (Blue), from institutions (Yellow) And Natural Resources (Green). Source: (Rao And Wilson 2022).

A central feature of the High-with-Low scenario is not just that innovation must occur but that it must accelerate. At a macro level, global improvement in energy efficiency (energy/GDP) will have to increase from its recent rate of -1.3% per year from 2016-21 to triple that rate from 2020-30 (IEA 2021). This in turn means an acceleration in rates of LED technology adoption from building efficiency retrofit and low-carbon heat technology adoption to vehicle substitution and active travel or shared mobility uptake.

The distinct characteristics of LED innovation also make it amenable to acceleration (Table 1). LED solutions tend to be smaller scale, more distributed, and more modular - what we call 'granular'. Smaller scale technologies show both faster learning (Sweerts, Detz et al. 2020) and more rapid adoption (Wilson, Grubler et al. 2020). In addition, the emergence of digitalization as a general purpose technology provides an array of new possibilities across sectors (Wilson, Kerr et al. 2020), particularly in terms of new services for heterogeneous end-user preferences and adoption niches.

Rapid learning in combination with the flexibility that granularity provides, may be especially important in providing new services to help populations attain decent living standards (Poblete-Cazenave, Pachauri et al. 2021, Semieniuk, Taylor et al. 2021). Granular LED solutions combine scalability with customization, so can better serve the rising demands for decent living that the LED scenario implies.

Table 1

Distinct Characteristics Of Innovation In The High-With-Low Scenario

Multiple attributes and new services. LED innovations do not simply replace energy-intensive practices but can provide multiple and novel services (Fishman, Heeren et al. 2021).
Many heterogeneous adopters. The diversity of individual preferences and local contexts matter, particularly in developing country contexts where pursuit of decent living standards shifts priorities and design trade-offs for innovation (Ockwell, Sagar et al. 2015).
Evolving social preferences. Some emerging indicators include shifts to valuing low-consumption lifestyles (Garnett, Balmford et al. 2019).
Peer and network effects. Being able to access information from trusted sources (peers) can mitigate risk aversion in technology adoption and can catalyse later stage epidemic-type technology adoption (Fletcher and Ross 2018, Wolske, Gillingham et al. 2020). Similarly network effects by which one person's adoption of a technology enhances the value of it for others can further accelerate innovation (Kubli and Ulli-Beer 2016, Li, Tong et al. 2017).
Small-scale, 'granularity'. Consequences of LED innovations being small scale (Wilson, Grubler et al. 2020) include lower adoption risk and more flexibility, especially with many heterogeneous adopters and of particular importance in DLS adoption contexts.
Many iterations. Technologies and behaviours can be expected to change and improve considerably leading to rapid learning (Nemet 2019). Short lifetimes of some LED innovations enable more rapid replacement of energy-intensive capital stock (Tong, Zhang et al. 2019) and an entry for novel LED practices in the medium-term.
Local system integration. Necessary for widespread uptake of LED innovations, while allowing for creative use of unique adoption contexts taking advantage of the flexibility that granularity provides (Jain, Qin et al. 2017).
Rebound effects. LED practices can become used so much that some of the resource-efficient gains are offset, although policy can mitigate this effect (Gillingham, Kotchen et al. 2013, Stern 2020).

Digitalization. Digitalization is a rapid and pervasive secular trend transforming society (e.g., media, networks, platforms) and the economy (e.g., automation, cloud-based services, artificial intelligence). Digitalization Has Large Potential Benefits For Sustainable Development (E.G., Collective Intelligence, access to opportunities, system efficiencies) but also major risks (e.g., value polarization, precarious employment, material resource extraction) (WBGU 2019). Harnessing digitalization as an enabler of LED transformation therefore requires clear direction, coordination and governance. Under appropriate conditions, **digitalization** can enable more services for fewer resource inputs in a High with- Low future (Table 2). Digitalization enables or creates new forms of resource-efficient services (e.g., shared ride hailing), new substitutes for physical activities (e.g., teleworking, online retail), new ways of organizing, sharing, and coordinating daily life (e.g., sharing economy platforms for waste reduction), and new opportunities for optimizing service provision (e.g., multi-modal transport systems).

Digitalization interacts strongly with innovation and decent living - the other two main themes of the High-with-Low scenario. Involving software and digital devices in service provision has the

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additional benefits of rapid innovation cycles through experimenting, testing, learning, and improving, that are associated with both digital and granular technologies.

Digitalization also enables many of the economic and social activities associated with decent living. Data-rich systems for providing or improving shelter, nutrition, health, socialization, and mobility allow for greater differentiation of services across diverse user groups and contexts. As examples: (1) mobility-as-a-service concepts allow different transport modes to be combined in real-time to suit users' particular travel needs; (2) e-health services bring specialist expertise to areas lacking healthcare infrastructure; (3) energy management systems added to existing homes and commercial buildings help control and reduce demand; (4) digital platforms improve social connectedness and rapid information dissemination on what LED solutions work.

Digital platforms also support community organizing to support service delivery (e.g., food-sharing networks or local food hubs) and retain employment opportunities in diversified service sectors (e.g., skills-matching platforms, P2P and sharing economy business models). Community-based service provision is an important alternative to centralized delivery models led by the state or public utilities in countries or contexts with low institutional trust or capacity.

Table 2

Examples of LED Solutions Dependent on Digitalization

Mobility. Shared vehicle fleets with higher occupancy rates and reduced trip times due to lower congestion are enabled by digital platforms connecting surplus capacity with real-time demands, and adaptively re-routing vehicles to maximise system efficiencies and occupancy rates (ITF 2017).
Mobility. Smart charging of electric vehicles provides a distributed storage resource for electricity network operators to draw on during peak periods in an 'vehicle-to-grid' configuration enabled by digital information flows and charging control systems (Thompson and Perez 2020).
Consumer goods. Dematerialisation through 'functional convergence' of multiple services and applications onto single digital devices (phones, tablets, laptops) acting as gateways to cloud-based service provision (WEF 2019).
Thermal comfort. Smart home technologies and home energy management systems configured to optimise heating and cooling for domestic comfort, maximise own-consumption of domestic electricity production, learn about domestic routines, and avoid wasted heating or cooling in occupied homes (AlFaris, Juaidi et al. 2017, Wilson, Hargreaves et al. 2017, Kloppenburg and Boekelo 2019).

Feasibility

The **feasibility** of a High-with-Low development pathway evidently depends on the evaluation criteria used, as well as subjective norms and values. We consider our High-with-Low scenario to be feasible for three reasons. First, it is in line with universally accepted principles of development and values such as those enshrined in the SDGs. Second, there is enormous unexploited potential to improve on current systems of service provision which are highly inefficient. Current systems at best deliver some 15% of primary resource inputs as useable services (TWI2050 2020). Step-

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change improvements are available in the efficiency of service delivery through new technologies, practices, business models, and form of market organization (e.g., service, sharing, or circular economies).

Third, although our High-with-Low scenario requires transformational change, it also offers numerous opportunities for new activities, products and services, and hence jobs and economic opportunity.

The High-with-Low development pathway sees a significant decoupling of resource use inputs from service provision outputs. A common counter-argument is that projected rates of decoupling far exceed historical precedent so are assumed to be infeasible (Semieniuk, Taylor et al. 2021). This argument is misleading for two reasons.

First, the empirical basis of historical energy intensity improvements is almost exclusively limited to economic indicators (energy use per unit of economic output like GDP) that typically improve by rates of 1-2 %/year. These are ill-suited for comparison with physical indicators (energy use per unit of physical service output like passenger-kms of mobility, lumens of light, etc.) that typically improve by 3-7 %/year. This difference is due to learning and cost reductions in end-use services (Nordhaus 1997, Fouquet 2010, Fouquet 2014). As the price of energy services falls rapidly, a dollar of input costs affords ever larger volumes of service. Conversely, using input prices and their aggregates like GDP to calculate economic energy intensity indicators yields lower rates of intensity improvement.

Second, intensity improvements historically have predominantly been achieved via technological efficiency improvements (more fuel-efficient vehicles, higher-efficiency light bulbs, etc.). Structural effects such as changes in modal splits or substitution of analogue by digital consumer goods have had either negligible or countervailing effects (e.g., shift from buses to private cars). Future decoupling of resource use from service provision can therefore be dramatically accelerated with associated structural change.

Risk

The ambition of the Paris Agreement and UN SDGs means any implementation pathway will be transformative and strongly discontinuous from historical trends. Feasibility of alternative pathways is therefore relative as well as absolute. We consider our High-with-Low scenario to be more feasible than alternative pathways that limit warming to 1.5 °C but with significantly higher resource use and reliance on large-scale, unproven technologies like carbon capture, storage, and removal (Fuss, Lamb et al. 2018). These include pathways in the 'shared socioeconomic pathways' (SSP) framework, widely used in IPCC assessments to characterize the uncertainty space for future emissions, but at (much) higher levels of energy demand (Scott, Smith et al. 2022). Such pathways are significantly more **risky** across development, environmental, and implementation risks.

Development risks can undermine the ultimate objectives or outcomes a given scenario aims to achieve. As an example, traditional high-growth economic development scenarios that fail to

consider distributional issues and equity come with development risks that high growth does not lead to high human development. The High-with-Low scenario's emphasis on inclusive and equitable development, with a focus on efficient service provision and decent living standards, leads to high human development without necessary reliance on high growth in economic output and resource use (GDP growth), thus minimizing development risks.

Environmental risks occur across multiple dimensions (e.g., climate, biosphere, water) as well as at multiple scales (local to global). Supply-side oriented development pathways that achieve climate objectives via planetary scale carbon-management mitigate climate risk while amplifying risks in other dimensions and scales (e.g., land-use conflicts, carbon storage sites, water needs). The High-with-Low scenario's avoidance of geoengineering options entails fewer environmental risks.

Implementation risks are associated with challenging, imperfect, or infeasible translation of a development pathway into action and practice. By lowering absolute resource use in the High-with-Low scenario, the portfolio of solutions is more diversified, benefits are more widely distributed, and more granular solutions enable faster experimentation, testing and improvements. This mitigates against implementation risks, in contrast to pathways relying heavily on a few large-scale centralized solutions like nuclear power, fossil fuel exploitation, bioenergy, or geoengineering-scale carbon capture and storage.

Rapid transformation

Speed is perhaps the most critical limiting resource given the twin urgency of the poverty eradication and climate protection imperatives. Our High-with-Low development pathway has several advantages over other pathways in relation to possible **speeds of transition.**

First, as a general rule, smaller-scale, modular, distributed, and less capital-intensive solutions ('granular') diffuse faster than capital-intensive and infrastructure-intensive large-scale centralized ('lumpy') solutions (Wilson, Grubler et al. 2020).

Second, people can change faster than infrastructures. Behavioral changes under appropriate incentives can be comparatively fast relative to large-scale technological infrastructures that turn over slowly (Grubler, Wilson et al. 2016). By relying more on distributed, people-centered changes, the High-with-Low scenario can achieve transitions over decadal time scales, compared to alternative pathways with centralized 'lumpy' solutions that do not leverage behavioral changes and unfold over much longer timescales (50-70 years).

Cross-Cutting Linkages Generating a High-with-Low Future

The three themes central to the High-with-Low scenario interact to generate a number of crosscutting linkages (Figure 3). In a High-with-Low future, these linkages are synergistic and supportive of resource-efficient outcomes and inclusive wellbeing. However, this is not deterministic, and indeed, one of these linkages relates to coordination and governance. In

alternative pathways for limiting warming to 1.5°C, cross-cutting linkages could generate inequalities, exclusion, extractive resource dependence, strong trade-offs between SDGs.

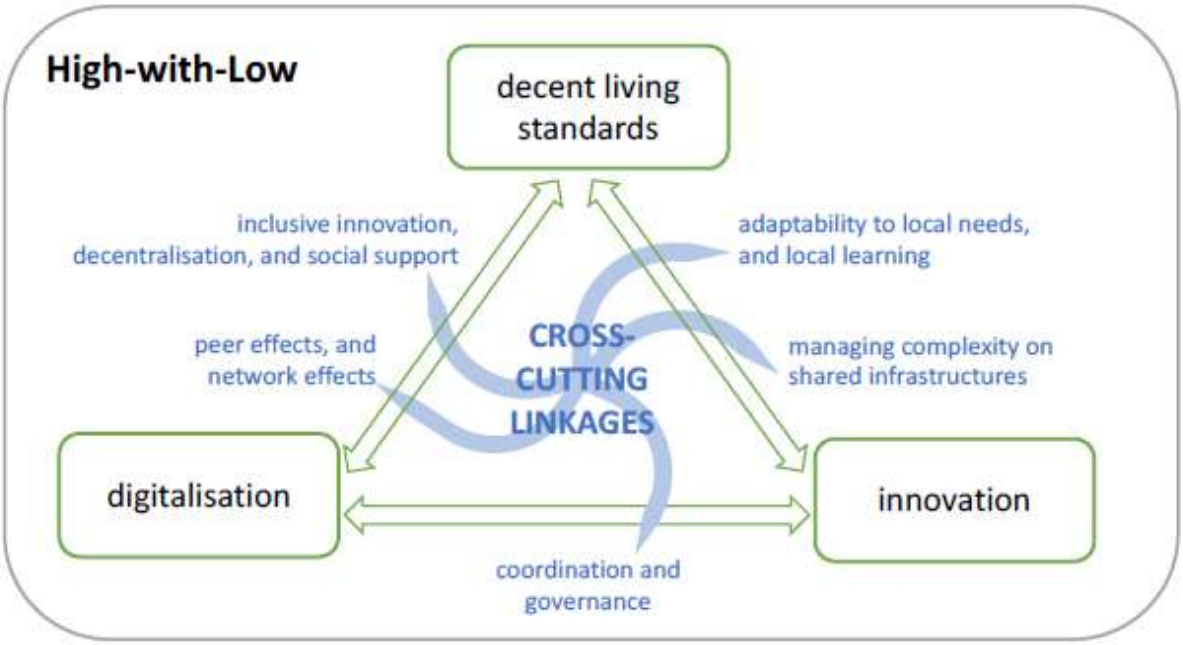


Figure 3. Cross-Cutting Linkages Between The Three Themes Of The High-With-Low Scenario.

Decentralization, inclusive innovation, and social support mechanisms

Appropriate innovation and digitalization enable multidimensional poverty eradication. As early as the 1970s, appropriate technology was seen as a way to deliver community empowerment and promote local ingenuity (Smith 2005). This followed from Boserup's work providing evidence of innovation processes in primitive agricultural settings, leading her to conclude: "*The power of ingenuity would always outmatch that of demand*" (Boserup 1976). More recently, the concept of **inclusive innovation** has gained traction: "*development and implementation of new ideas which A spire to create opportunities that enhance social and economic well-being for disenfranchised members of society*" (George, McGahan et al. 2012). Similar concepts, such as frugal innovation, have also been highlighted in the literature as important for repurposing existing resources or using locally abundant or discarded resources to deliver low-cost services to meet needs of remote and low-income populations affordably (Hossain 2022).

Within a High-with-Low futures framing, achieving DLS for all requires rethinking innovation processes and harnessing digital technologies for this purpose. This has three main elements: decentralization; inclusive innovation; and social support mechanisms.

First, there is a need to re-examine the role of incumbent large-scale centralized modes of infrastructure and service delivery that have tended to concentrate benefits and become inert to change. A shift from the existing top-down supply-focused privatization and commoditization of knowledge to more inclusive forms of innovation that harness local ingenuity will be required.

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High with-Low innovation includes that which originates from, and operates in, civil society. This is more localized, context specific, and socially determined. In a High-with-Low future, more granular technologies and more **decentralized** service-provisioning systems allow for greater diversity and choice in modes of provisioning, and an agility that can accelerate DLS for all.

Second, service provisioning to meet DLS for all has to be more **inclusive** for both consumers and producers or suppliers. A larger role for community-based organizations, social enterprises, and prosumers (actively participating end-users) can extend services and integrate excluded populations.

A good example is in how low-cost solar-based lighting technologies and solar panels are diffusing widely in sub-Saharan Africa. In Bangladesh, 'swarm electrification' approaches allow for the linkage of individual stand-alone energy systems to form microgrids that can eventually even interconnect with national or regional grids (Dumitrescu, Groh et al. 2020). This inclusive form of innovation shows how network effects are generated through the inclusion of localized economies with strong producer-consumer linkages embedded within larger systems of trade and exchange.

Digitalization can also support and enable sharing economy practices and user-led innovations that can help reduce or avoid waste by redeploying surplus capacity in real-time (e.g., ridesharing, shared ride-hailing, P2P carsharing, crowdsourced finance or work-time resources, food sharing, community fridges).

More broadly, digitalization also has the potential to democratize the provision of DLS. For instance, e-learning and e-health platforms can enable information flows and more equitable access to public services (e.g., mobile-based reminders to patients to take medication, greater interaction with teachers and health professionals) (Sharma and Sturges 2007). Digitalization can also support new processes, increase efficiency and transparency, and allow for participation in existing markets and processes, and thus drive competitiveness and shape patterns of development towards greater equity, inclusiveness and sustainability (Figueres 2013). Specific examples include the use of mobiles by remote micro-entrepreneurs to contact customers (Donner and Escobari 2010).

Third, although innovation and digitalization can help make services more affordable, short-term subsidies or **social support mechanisms** will still be required to ensure access for all. Business model innovation is also needed to convert prohibitively-high upfront costs into smaller streams of payment. Examples of this already happening is visible in Africa and other developing regions with mobile-based apps such as M-Pesa and Hello Tractor which are enabling greater access to financial services that were out of reach for remote, underserved, or low-income communities (Table 3).

Appropriate governance institutions or coordination mechanisms are also needed to avoid exploitative practices in the sharing economy (Acquier, Daudigeos et al. 2017). Digital platforms benefiting from strong network externalities leading to dominant market positions (e.g., AirBnB,

Uber) move away from principles of sharing surplus resources to market-logics of new private service provision (Frenken 2017).

Table 3

Examples Of Innovations Harnessing Digitalization To Support Dls For All

Hello Tractor. The so-called 'Uber for farmers', Hello Tractor aims to provide many agricultural workers with access to previously unaffordable technology. It is a mobile phone app through which farmers can hire mechanized farming equipment in several African nations.[1]
M-Pesa. A financial service, developed in Kenya, allows mobile device users without bank accounts access to: credit and savings; payment for products and services; and deposits, withdrawal and transfer of money from a network of agents that includes airtime resellers and retail outlets acting as banking agents. Its positive effects include creating money flows to rural areas, where cash is difficult to access and increasing the financial autonomy of women (Morawczynski and Pickens 2009).

Adaptability to local needs, and local learning

LED climate solutions tend to be demand-focused, human-scaled, and 'granular' (low unit cost, modular). Examples include: efficient buildings, clean vehicles, non-motorized and shared mobility schemes, efficient appliances, distributed supply technologies like PV panels, fuel cells, and batteries. Smaller unit scales enable rapid experimentation and learning, as well as adaptation possibilities to diverse market and social conditions. Bespoke, customized solutions that can be locally adapted to diverse user needs allow for experimentation, learning, and so rapid innovation and improvement cycles that further widen applications in diverse markets and adoption environments.

Customization and local learning involves the adaptation of globally generated innovations (both hard and soft) to the needs and idiosyncrasies of local adoption contexts. Benefits are often multiple and valued differently among adopters. This adaptation typically involves a process of local learning, in which a variety of actors pay a role in integrating novelty into the local culture, behavior, and technological systems. A particular focus is to reorient local learning to the diverse set of needs around supporting DLS. It raises questions about how innovation systems can evolve to harness local knowledge. Rapid learning in combination with the flexibility that granularity provides may be especially important in providing new services to help populations attain DLS (Poblete-Cazenave et al. 2021; Semieniuk et al. 2021). Digitalization means that small pilot examples oriented toward DLS can be improved, scaled-up quickly, and transferred to other locales, for example via sharable computer code, product designs, and easy language translation.

At the same time, innovation processes with increasing returns to scale, and digitalization with its characteristic network effects, are dependent on standardization and serialization for rapid dissemination through replication as already evidenced in PV and battery technologies. But the granular nature of these technologies still allows for their adaptation to diverse settings including market sizes (magnitude of local energy demand), system configurations (local energy networks),

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consumers' engagement (prosumers), or innovative financing opportunities (cooperatives or crowd funding schemes). This enhances their social legitimacy and acceptance, supporting accelerated diffusion.

Peer effects, and network effects

Realizing the potential of LED innovation depends on speeding up the processes of technology development, adoption, and integration with surrounding technological systems and infrastructures, such that the beneficial impacts are pervasive and inclusive. Accelerated LED innovation can initiate via catalytic mechanisms (Catalini and Tucker 2016, Farmer, Hepburn et al. 2019) and scale via increasing returns (Arthur 1989, Ma, Grubler et al. 2009). Examples of catalytic mechanisms include peer effects, and examples of increasing returns include network and learning effects (Kubli and Ulli-Beer 2016, Li, Tong et al. 2017). An iterative process of experimentation can occur locally and address the diverse set of needs to support DLS.

First, peer effects, enabled by digitalization, facilitate the recognition and communication of the benefits of LED practices among typically risk-averse adopters (Guadalupi 2018, Wolske, Gillingham et al. 2020). Being able to access information from peers as trusted sources can mitigate risk aversion in technology adoption (Rai and Robinson 2013) and in later stages can catalyze epidemic-type technology adoption if experiences communicated through inter-personal networks are positive (Fletcher and Ross 2018, Wolske, Gillingham et al. 2020). Peer effects reduce barriers to adoption by providing easy to access trusted information about LED innovations (Qiu, Yin et al. 2016). Peer effects have been observed both in terms of assessing outcomes (Bollinger and Gillingham 2012, Korcaj, Hahnel et al. 2015) and also by directly asking about them as a motivation (Palm 2017). Digitalization facilitates catalytic and increasing adoption dynamics via granularity and flexibility, in addition to enhancing knowledge flow directly (through electronic word-of-mouth, social media). LED innovation extends well beyond hardware, and peer effects are central to initiating a catalytic process of adoption (Catalini and Tucker 2016). In pursuit of DLS, peer effects have also been important among low-income adopters but have required policy to catalyze (O'Shaughnessy, Barbose et al. 2021).

Second, network effects, enhanced via standardization create the potential to accelerate low-energy demand innovation by increasing the appeal of LED behaviors and systems over time. Digitalization provides the driver for connectivity and interoperability to enhance the value of LED as it attains scale and more users (Kubli and Ulli-Beer 2016). For example, aggregating these systems to the scale of smart cities where "connected intelligence" underlies many aspects of daily life creates increases adoption of LED behaviors as more people engage with the system (Komninos 2019). The value of peer to peer energy trading among households increases with users (Morstyn, Farrell et al. 2018). Scale can help with standardization, a prerequisite for network effects.

Dominant designs, interoperability protocols, open data protocols, and shared platforms all make adoption easier and more appealing. Regulation and investment in both hard and soft infrastructure

are likely necessary to reach the scale needed for network effects to emerge, and to avoid fragmentation of data-enhanced services into private commercial silos (Doblinger, Dowling et al. 2016).

Managing complexity on shared infrastructures

Services for inclusive wellbeing depend on provisioning systems (firms, supply chains) and infrastructures (transport, energy, utilities). In our High-with-Low future, innovation and digitalization combine to enable the balancing and managing of increasingly complex resource flows (e.g., electricity networks), the effective use of shared infrastructure (e.g., transportation).

First, digitalization also enables the integration of high shares of intermittent renewable generators(wind, solar) onto electricity networks, and the balancing of this variable supply with large volumes of distributed storage and demand flexibility resources (EVs, demand response, smart controls, internet of things) (IEA 2017). Digitalization is therefore strongly linked to rapid electrification as a robust strategy for climate change mitigation across all 1.5°C pathways (Rogelj, Shindell et al. 2018). In the LED scenario, electricity provides over 50% of final energy by 2050, with wind and solar contributing around half of total primary energy (Grubler, Wilson et al. 2018).

Second, digitalization can help optimize the resource-efficiency of service provisioning systems using real-time data sensing and analytics to match needs with available resources (e.g., freight and delivery logistics, precision agriculture, digital twin simulations of infrastructure systems, circular economy material flows). Contexts in which private firms compete to provide services to end-users need to be carefully managed to ensure overall system efficiency. For example, a coordinated and integrated shared and public mobility system optimised to deliver intra-urban mobility needs requires a fraction of the vehicles on the road in today's cities (ITF 2017, Moon 2017). But an uncoordinated mosaic of private shared and micro mobility providers, each with bespoke platforms, competing with and cannibalizing high volume public transport routes, has the opposite desired effect (Creutzig, Franzen et al. 2019). Governance institutions are needed to coordinate the activity of competing digital providers so as not to undermine public purpose aims.

Coordination and governance

Each of the three themes within High-with-Low have important implications for governance institutions and coordination mechanisms to corral a highly distributed programme of transformation towards High-with-Low goals.2

For **decent living standards**, a greater degree of coordination and regulation of basic infrastructure will be needed for it to expand rapidly, at least initially. This is the responsibility of public authorities and institutions, and is important for ensuring:

- Interoperability among providers and provisioning systems;
- Accessibility of private individual and community service providers to the market, i.e., allowing for a range of new entrants;

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• End-user and consumer rights protection;

Where existing distributions are very unequal, redistribution may be required, specifically in the case of very resource-intensive or environmentally-damaging services (e.g., private automobility).

For **innovation**, policy, regulation and governance can be both an enabler of innovation diffusion as well as an inhibitor. A set of directions for the public sector to facilitate LED pathways include:

• Creating shared expectations of a High-with-Low future through a broad mix of policies to support LED innovation that are comprehensive in scope, and ultimately need to be local in their implementation to reflect heterogeneous adoption contexts, while including an emphasis on the design of choice architecture.

• Orienting innovation toward inclusion and decent living standards by: easing access to technology, including financial and intellectual property; reducing barriers, such as up-front costs; targeting broad affordability; and making disruptive design and production compromises.

• Enhancing standardization and interoperability including through new business models that can make use of shared standardized platforms, while remaining open themselves to complementary innovations. Enable access through capacity utilization.

• Fostering competition and avoiding risks of monopolies by stimulating novelty, entrepreneurship, and new services while limiting firm creation of barriers, rents, and monopolistic or oligopolistic practices and pricing.

• Moderating rebound to avoid LED solutions enabling more excessive consumption, and encouraging re-use of shorter-lived devices to encourage circularity.

• Iterating through policy experimentation, innovation, and diffusion by using supportive rules, subsidies, taxes that can be introduced and evaluated to identify successful policy models. Standardization of high performing policies can be transferred to other jurisdictions, and then adapted for specific of local context. This process would take full advantage of the flexibility that granularity provides and the natural experiments that heterogeneity supports.

• Acting as trusted information brokers to support for social network diffusion processes.

For **digitalization**, innovative activity needs clear direction towards public purpose to ensure it is aligned with decent living outcomes. Absent effective regulation, private service providers will seek to collect, hoard, commoditize, and exploit data about user preferences and behaviours. Digitalization’s winner-takes-all networks and platforms lead to market dominance. However these monopolistic practices give the cities, regulators and governments the opportunity to enforce a 'social compact' or 'social license to operate' - i.e., continued market access in exchange for open

data, public benefits, tax contributions to support the education and infrastructure on which digital services depend, and space for a wide variety of actors including local entrepreneurs, civic groups,

and public organizations to remain actively involved in developing, trialing, rolling out, and competing to provide digital services across the different dimensions of decent living. As examples, policies, rules, regulations, norms, and other governance institutions for digital LED solutions should:

- Collect and analyze data on usage patterns to manage potential rebound effects;
- Integrate new forms of private service provision with public infrastructures to ensure overall system performance in meeting human needs;
- Ensure digital citizenship standards that empower users with data rights and avoid predatory data harvesting that undermines agency and social institutions;
- Facilitate universal access to digital skills and infrastructure, regardless of location, income, employment, or age.

From Scenario Narratives to Quantitative Modelling of High-with-Low Futures

The High-with-Low scenario narrative aims to provide a rich explanation of why and how a resource-efficient future with high levels of wellbeing is achievable. Quantitative interpretation of this narrative using sectoral and energy system modelling tools further enriches understanding of policy levers, outcomes, distributional effects, and pathways over time. This quantitative step invites modelers to select inputs, parameters, constraints, and model processes that are consistent with the High-with-Low scenario narrative. These will vary widely across models of different scopes, scales, solution algorithms, and purposes. While it is not possible to generate a single set of quantitative parameters for modeling High-with-Low futures, certain guidelines provide entry points, boundary conditions, or recommendations for supporting modelling efforts.

Ensuring High-with-Low modelling is consistent with structural change assumptions and energy intensity improvements

To make transparent the decoupling of resource inputs from service provision outputs in the High-with-Low scenario, we have developed a simple accounting tool called DETRAS. This is based on an extended decomposition analysis of final energy use into activity (A), structure (S), and intensity (I). The full DETRAS tool, with accompanying documentation, is available from the authors on request.

Figure 4 illustrates the results for two macro-regions (Global North and Global South) in a revised version of the global LED scenario (Grubler, Wilson et al. 2018). The first "user adjusted" analysis treats end-use sectors and service-related activities as independent from one another. So, for example, urbanization is a scenario driver that affects urban form, mobility needs, dwelling size, and so on, but this is implemented top-down and exogenously on each sector independently. The

second "linkages/DLS" analysis includes inter-sectoral linkages as well as explicit consideration of energy needs for meeting decent living standards (DLS). So, for example, more compact urban form and higher density buildings lead to reductions in private motorized mobility, with these linkages being implemented endogenously and horizontally between sectors.

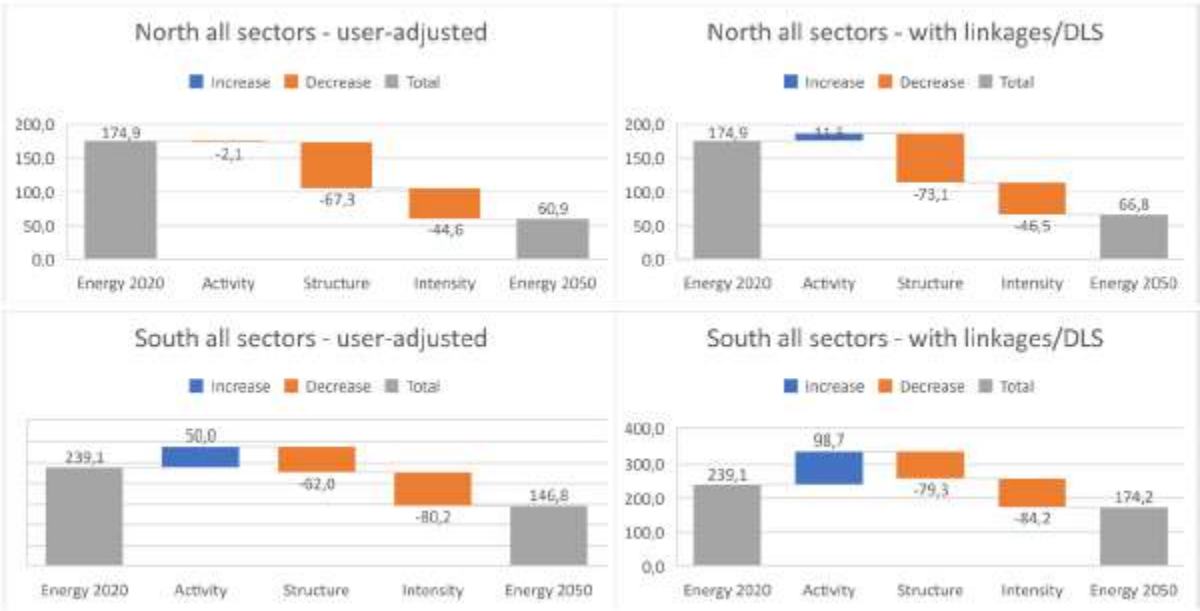


Figure 4. Changes in Final Energy Use From 2020 to 2050 Decomposed into Activity, Structure, and Intensity Components in a High-With-Low Scenario, Distinguishing: (1) Global North (Upper Panels) And Global South (Lower Panels); (2) User-Adjusted Global LED Scenario (Left Panels) And Inter-Sectoral Linkages and DLS Scenario (Right Panels). All Units in Jed/Yr

Figure 4 (grey bars) shows that a High-with-Low transition in both global regions is associated with absolute reductions in final energy use between 2020 and 2050. However, the underlying drivers are markedly different, as is made clear by the decomposition of change into the A-S-I components. In the Global North (upper panels), there are only modest increases in activity levels, with decoupling from resource (energy) use predominantly achieved by structural change (-73 EJ) with additional and complementary energy intensity improvements (-47 EJ). In the Global South (lower panels), activity levels rise substantially, particularly as a result of providing universal decent living standards (+49 EJ). The absolute decoupling of final energy use from rising activity levels is achieved roughly half due to structural changes (-79 EJ) and half from energy intensity improvements (-84 EJ). For scenarios and modelling studies with different regional disaggregation compared to the original LED scenario we provide the following recommendations:

- Use the DETRAS accounting framework and modify the spreadsheet with your own region/scenario values for 2020 and 2050.
- Compare the decomposition factors in your scenario to that for global LED at the aggregate level

(all sectors) and *either* provide a descriptive narrative to explain any significant deviations in activity-structure-intensity dynamics (Figure 4) *or* iteratively modify your scenario using the "user-adjusted" feature in the DETRAS tool.

- Repeat the previous step for each end-sector or activity as documented in the DETRAS framework, and revise and document cases of significant departures from the structural change characteristics of the global LED model.

Ensuring High-with-Low modelling is consistent with activity levels and energy requirements to provide decent living standards for all

Modeling the High-with-Low scenario can draw on and benefit from extensive quantitative assessments of decent living standards (DLS). Table 4 makes explicit the underlying assumptions on activity levels and energy intensities assumed for meeting each dimension or component of DLS. Table 5 shows estimated per capita energy gaps to meet DLS for all at a regionally disaggregated level and broken down by each major DLS dimension. These gaps measure the difference between existing levels of energy use for DLS-related goods and services, and levels of energy use required to achieve DLS for all by 2050. This defines a minimum threshold by which energy per capita would need to rise to ensure consistency with the High-with-Low assumptions on DLS. Note, however, that these gaps do not assume any major technological or structural changes which may reduce energy use for specific DLS dimensions (e.g., digitalization as an enabler of e-mobility, e-health, education).

The data in Table 4 and Table 5 provide target outcomes against which modeling efforts focused on raising living standards can be iteratively tested. Using typical per capita values of alternative service provisioning systems (e.g., from the DETRAS framework) can illustrate the effect of structural change and efficiency improvements on lowering the current energy intensities of DLS (Table 4). These can be substantial. In addition, alternative service provisioning (e.g. shared mobility as opposed to privately owned vehicles) can also substantially lower the costs of service provisioning and thus increase the feasibility and timing of providing DLS for all. For example, a simple assumption of a minimum share of 40% public transport in every region, in comparison to the current split between private and public transit implies a 9% lower energy requirement to provide decent mobility services for all globally (Kikstra, Mastrucci et al. 2021). For the single region of North America (NAM), this difference between simulations with the existing modal split and the higher 40% public transport share is as much as nearly 5 GJ/cap/yr in 2050 (Kikstra, Mastrucci et al. 2021).

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Table 4

Activity Levels and Energy Intensities for Providing DLS for All.
Adapted From: (Kikstra, Mastrucci et al., 2021)

DLS Dimension	Activity	Construction Energy Intensity	Operational Energy Intensity
Nutrition	1653-2066 kcal/cap/day	–	0.8–6.6 MJ/kcal
Cooking	1/hh	0.047 GJ/app	2.2 GJ/app/yr
Cold storage	1/hh	3.8 GJ/app	0.58 GJ/app/yr
Housing	2.1-8.7 cap/hh with 10.1-14.7 m^2 floorspace/cap	3.3 GJ/m^2	–
Thermal comfort	10.1-14.7 m^2 floorspace/cap	1.2 GJ/unit (cooling) 1.2-1.3 GJ/unit (heating)	0.0–88.3 MJ/m^2/yr (cooling) 0.0–1110.8 MJ/m^2/yr (heating)
Water	65 l/cap/day	0.24 KJ/l	2.36 KJ/l
Water heating	30 l/cap/day	-	1.1-3.2 GJ/cap
Sanitation	Provided to all	2.9 GJ/cap	443 MJ/cap/yr
Clothing	2.4 kg/yr (global North) 1.3 kg/yr (global South)	-	129-744 MJ/kg
Footwear	0.9 kg/yr		38-217 MJ/kg
Health	$1024/cap/yr	-	3.03 GJ/$
Education	$1093/student/yr (primary) $2224/student/yr (lower secondary)		
Phone	1/hh	110 MJ/phone	28 MJ/phone/yr
Bigger screen	1/hh	0.99 GJ/television	0.72 GJ/television/yr
Mobility	8527 pkm/cap/yr (rural = 1.24*urban)	0.009 MJ/p.km (bus) 148 GJ/unit (car) 0.035 MJ/p.km (rail) 7.9 GJ/unit (2-3 wheeler)	0.21-2.0 MJ/p.km (bus) 1.0-2.5 MJ/p.km (car) 0.10-0.96 MJ/p.km (rail) 0.54-1.7 MJ/p.km (2/3-wheeler)
Roads		3.8 TJ/km	–

Table 5

Energy Gaps for Providing Five Dimensions of DLS for all in Eleven World Regions. Adapted From: (Kikstra, Mastrucci Et Al. 2021).
Region Acronyms: AFR = Subsaharan Africa; CPA = Centrally Planned Asia; EEU = Eastern Europe; FSU = Former Soviet Union; LAM = Latin America; MEA = Middle East & North Africa; NAM = North America; PAO = Pacific Islands & Oceania; PAS = Pacific Asia; SAS = South Asia; WEU = Western Europe.

Energy gap in GJ/capita to meet five dimensions of decent living by 2050						
Region	**Health**	**Mobility**	**Nutrition**	**Shelter**	**Socialization**	**Total Gap**
Sub-Saharan Africa (AFR)	3.27	5.79	0.50	0.84	0.97	**11.37**
Centrally Planned Asia (CPA)	2.25	3.86	0.72	1.31	0.20	**8.34**
Eastern Europe (EEU)	0.61	2.26	0.00	0.72	0.07	**3.66**
Former Soviet Union (FSU)	1.48	4.40	0.01	0.00	0.19	**6.08**
Latin America (LAM)	1.24	3.77	0.35	0.17	0.32	**5.85**
Middle East & North Africa (MEA)	1.57	5.70	0.12	0.04	0.04	**7.47**
North America (NAM)	0.00	2.02	0.01	0.00	0.00	**2.03**
Pacific Islands & Oceania (PAO)	0.00	1.89	0.09	0.00	0.02	**2.00**
Pacific Asia (PAS)	2.05	3.90	0.39	0.85	0.28	**7.47**
South Asia (SAS)	3.34	1.96	0.40	1.18	0.54	**7.42**
Western Europe (WEU)	0.02	2.38	0.00	0.00	0.00	**2.40**

Ensuring High-with-Low modelling is consistent with innovation processes and technology adoption dynamics

State-of-the-art energy modelling tools still have only weak representations of the peer effects, network effects, and customization potentials for LED technologies, which are at the intersection between decent living, innovation, and digitalization.

First, peer effects are a prominent feature of agent-based modelling tools that allow for social interactions and information exchange through social networks (Rai and Robinson 2015, Zhuge, Yu et al. 2020). However, they rarely feature in sectoral, systems, or process-based integrated assessment modelling used to project long-term transformation pathways such as High-with-Low. Recent global studies have parameterized social influence within global integrated assessment models to explore the effect of social learning on the adoption of low-carbon technologies like electric vehicles (McCollum, Wilson et al. 2018). Peer effects and technological learning have a mutually reinforcing effect on cost reductions and performance improvements that accelerates change (Edelenbosch, McCollum et al. 2018). However, these attempts to endogenize peer effects are the exception not the rule.

Second, network effects are included only in the sense of enabling infrastructure such as electricity networks (e.g., aggregation of disparate loads which leads to higher load factors and more efficient infrastructure utilization). But these are not simulated at urban scales, for example, in which infrastructure for shared mobility could expand mobility choices. Distinct from learning effects,

network effects stimulate adoption as the value of innovations increases with the number of users. For example, a discrete-choice model of electric vehicle adoption shows that positive feedback effects support further adoption as charging infrastructure expands (Li, Tong et al. 2017).

Third, the opportunities created by granular LED technologies for customization and learning-by doing across different DLS niches are not captured in modelling tools. Technologies tend to highly aggregated and uniformly represented across adoption contexts (e.g., in cost, performance, energy system interlinkages). The closest approximations to local distinct niches are from input prices (e.g. fuels) that can vary regionally.

Peer effects, network effects, and customization are essential for accelerating improvement and adoption of LED technologies as they interact to generate non-linear effects. For example, with peer effects, a small initial stimulus can catalyze much larger adoption. Network effects can generate increasing returns at higher levels of adoption. Customization can generate entirely new markets. Learning-by-doing can deliver better and lower cost technology to contribute more adequately to expanding access to DLS.

Modelling of High-with-Low futures therefore needs to find ways to more explicitly characterize these dynamics. As examples:

- *Peer effects*. Once stimulated, peer effects can generate non-linear growth in adoption. But they need to be carefully calibrated to determine which stimuli actually produce peer effects and which stimuli have no effects. In reality this outcome probably emerges from a largely stochastic process.
- *Network effects*. The possibility of network effects, particularly in urban systems, raises the question of whether we need city-scale objects in modelling simulations of High-with-Low futures. Further needs for disaggregation result from some locations having more absorptive capacity than others because of infrastructure and especially coordination and standards (see above section on governance).
- *Customization*. The potentially important role for local adaptation and customized implementation of generic components implies that more differentiation of LED approaches will be needed. These customized LED solutions are highly amenable to learning and thus their costs and adoption should be endogenous and dynamic.

For each of these real world data sets are important for calibration. For regional and sectoral modelling of the High-with-Low narrative, we suggest two alternative formulations: one along the lines of current supply-focused modelling practice with no peer effects, no network effects, and standardized solutions delivered via centralized business models and infrastructures; and an alternative High-with-Low approach which is end-user focused, distributed, and with customized solutions with peer and network effects. These two contrasting perspectives should then be further described in terms of their innovation and learning effects (leading to cost reductions) as well as their adoption dynamics (e.g., market penetration rates). Using historical analogues as well as scenario comparisons (e.g., LED vs. SSP2) can serve as a guide to further distinguish the dynamics of supply-focused modelling versus High-with-Low. As an example, cost improvement rates for

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granular solutions in High-with-Low would typically be up to 20% per doubling of cumulative experience, whereas for large-scale centralized solutions in supply-focused modelling, cost reductions would be much more modest due to limited learning and experimentation effects (e.g., 0-5% per doubling of cumulative experience). Similarly, adoption rates for granular, distributed solutions in High-with-Low could achieve 80% replacement of a given capital stock within 10-15 years (e.g., shared mobility schemes). In contrast, adoption dynamics for large-scale centralized solutions would follow more historical trends, ranging between 30-50 years for an 80% replacement in end-use technologies (e.g., fuel cell trucks) and slower still for lumpy capital intensive upstream supply infrastructures such as hydrogen.

Because so many of the dynamics are non-linear we should expect many different possible outcomes and configurations. In other words, modelling results will be less deterministic than without these effects. Scenario and modelling analysis of High-with-Low futures should therefore refocus away from singular, optimal pathways and towards the combinations that give the highest probability of achieving full potential of LED options.

Ensuring High-with-Low modelling is consistent with digitalization impacts on activity and energy use

Digitalization has potentially large but uncertain impacts on energy and material use. Taxonomies distinguish direct, indirect and systemic impacts (Horner, Shehab et al. 2016). Indirect impacts of digital services or applications can reduce energy use (e.g., efficiency, optimization, management, control) or increase energy use (e.g., direct or indirect rebound, intensification, novel applications).

The balance of evidence historically suggests that efficiency gains from digitalization have been more than offset by scale and growth effects resulting from digitally-enabled productivity; consequently digitalization has increased energy demand (Lange, Pohl et al. 2020). The High-with- Low scenario narrative harnesses digitalization for resource-efficient service provision while mitigating and minimizing risks of rebound.

For modelers implementing discrete digitally-enabled LED innovations for specific end-use services or sectors, recent reviews provide reference points for the potential changes in activity, energy or carbon emissions that can be expected. Figure 5 shows the net effects of a range of end user-oriented digitalization solutions which include the risk of increased emissions due to inefficient substitutions, induced demand, and rebound effects (Creutzig, Roy et al. 2022). Figure 6 shows similar effects of digitally-enabled technologies and practices in the home that are consistent with High-with-Low narrative and outcomes; similar quantitative syntheses are available for mobility and food-related innovations from the same source (Wilson, Kerr et al. 2020).

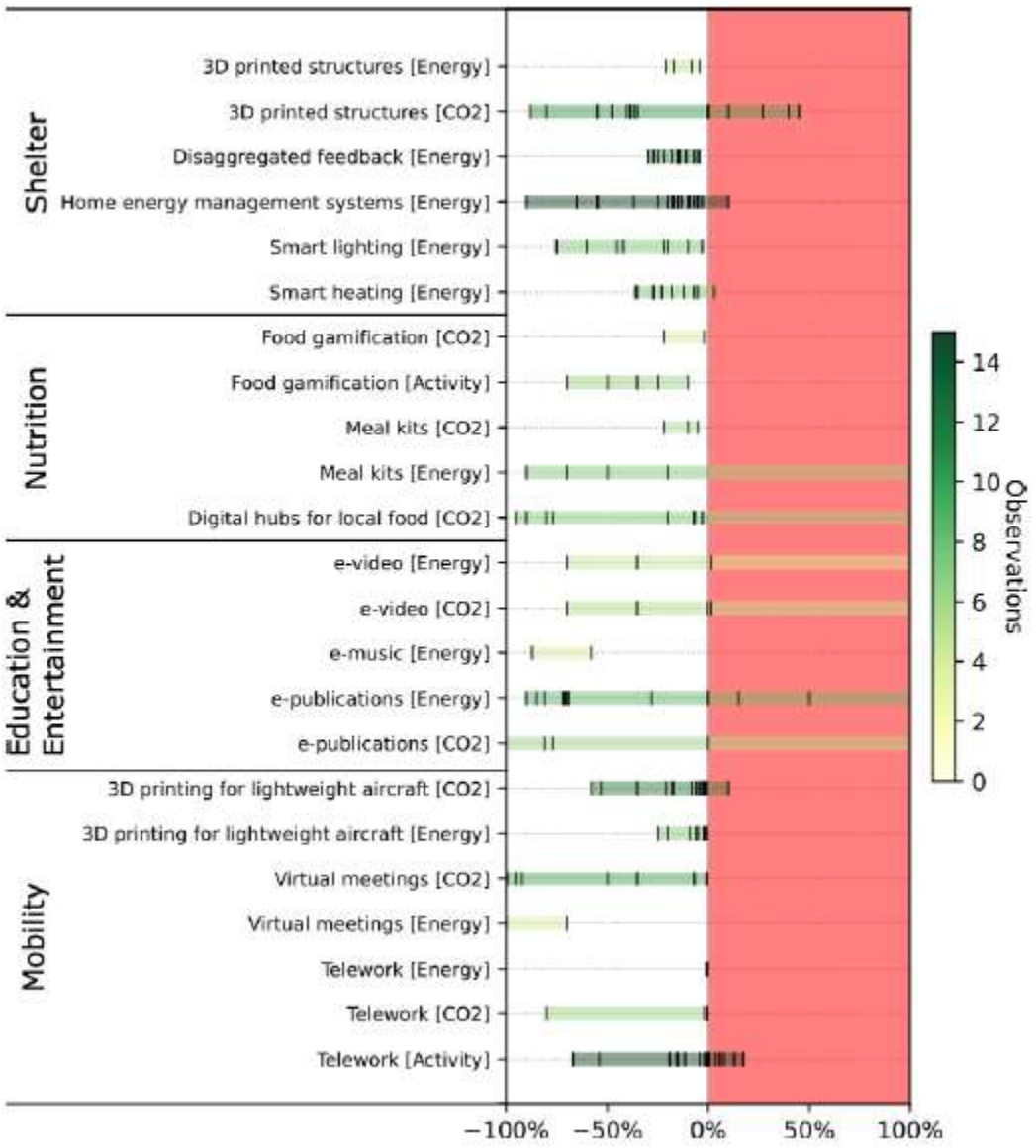


Figure 5. Studies assessing net changes in CO2 emissions, energy use, and activity levels indicate mitigation potentials for numerous end user-oriented digitalization solutions, but also risk of increased emissions due to inefficient substitutions, induced demand, and rebound effects. 90 studies were assessed with 207 observations (indicated by vertical bars) including those based on empirical research, attributional and consequential life-cycle assessments

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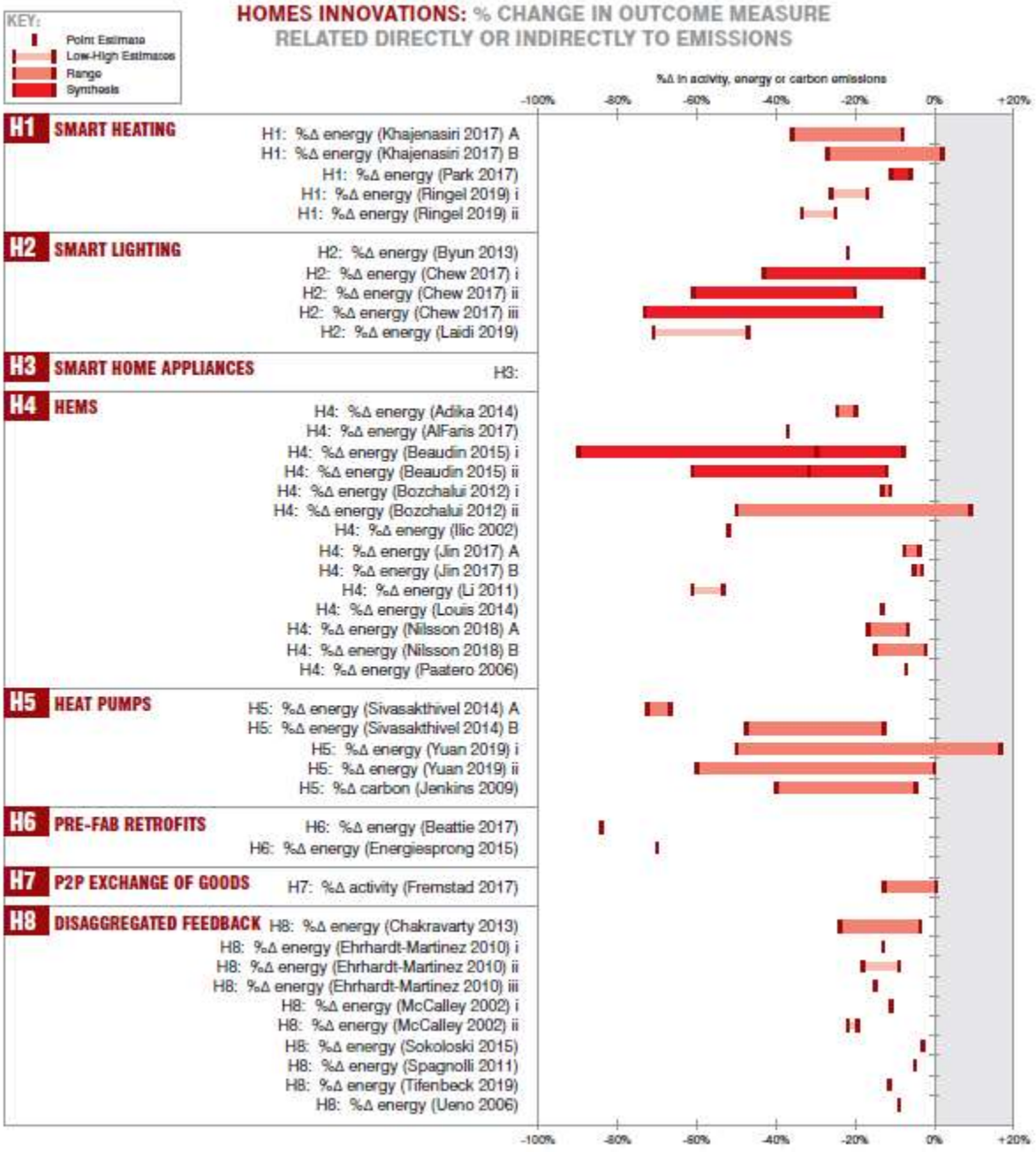


Figure 6. Synthesis of Estimates of Net Changes In C02 Emissions, Energy Use And Activity Levels as an Indicator of Mitigation Potentials From Digitally-Enabled Led Technologies In The Home.
Note: Similar Estimates Are Available For Digital Mobility And Food Innovations. Source: (Wilson, Kerr et al., 2020).

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3. EMF 37: Deep Decarbonization & High Electrification Scenarios for North America[2]

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?

[2] This section draws heavily and quotes freely from Eenergy Modeling Forum (2022).

- 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 37 has engaged in a multi-round study that encourages the participation of economy-wide[3] and more detailed sectoral models. EMF 37 includes study groups focused on transportation, buildings, industry, and carbon management, with the possibility of adding cross-cut groups on other important dimensions (e.g., electricity, hydrogen, ancillary impacts, bioenergy, trade, and distributional / equity outcomes). As with any 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 6 below presents the process through a beta and two full rounds of scenario development, modeling, data submissions, and analysis. 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 completed a 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 helped us begin the dialogue between the modeling teams and the study groups and informed the design of scenarios for Rounds 1 and 2.

EMF 37 would like to expand the model participation beyond economy-wide and energy system models to include detailed sectoral models where possible. To include sectoral models while maintaining important consistencies within the study, a critical deliverable from the economy-

[3] As used here, economywide includes both general and partial equilibrium models with comprehensive energy sector coverage.

wide all energy models include 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. Initial discussions of the details and timing of these data passes began during the beta round and will continue to be refined as the study progresses.

While we are not including a full third round for this study, given the complexity of the scenarios and data dependencies between models, the study groups will have an opportunity for additional data submissions after the final submission deadline for inclusion in the overview paper.

The anticipated study schedule, presented in Table 6 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.

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*.[4]

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 2. The remaining required Round 2 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).

[4] 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.

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Table 6
Updated EMF 37 Study Schedule

Round	Month	Meeting Focus	Objectives
kick-off	29-Oct-20	overview and process	
beta round	11-Dec-20	economy-wide initial scenarios	Present initial beta round results from subset of economy-wide models. Discussion of results with modelers and study group experts. Initial discussion of round 1 scenario specifications.
	08-Jan-21	carbon management	Beta round results from study group models. Questionaire Discussion. Discuss data study group can use from economy-wide models. Discuss data study group can provide to economy-wide models. Round 1 scenario specification discussion.
	12-Feb-21	transportation	
	12-Mar-21	buildings	
	09-Apr-21	industry	
	14-May-21	economy wide beta round scenarios	Overview presentation of full beta round results from economy-wide models. Plan for data exchanges between subgroups and economy-wide models. Discuss potential model improvements. Round 1 scenario specifications final discussion.
	11-Jun-21	economy wide beta round scenarios	finalize round 1 scenarios, data template, data hand-off, model improvements, round 1 data submission due before firs tround 1 meeting
round 1	27-Sep-21	Round 1 kick-off	SC provide 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 SG scenarios.
	05-Nov-12	***BETA ROUND SCENARIOS DUE***	
	19-Nov-21	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.
	07-Jan-22	***ROUND 1 OVERALL SCENARIOS DUE*** *(SG scenarios accepted)*	
	21-Jan-22	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.
	04-Feb-22	Scenarios and Data Help Session	Open "Office Hours" to discuss scenarios and data template issues
	03-Mar-22	***ROUND 1 SG SCENARIOS DUE*** *(Overall scenarios revisions accepted)*	
	18-Mar-22	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.
	08-Apr-22	Industry and carbon management deep dive	
	22-Apr-22	*All ROUND 1 scenario revisions accepted*	
	06-May-22	Discuss modelling and scenario changes for round 2	Present/Distribute revised key figures reflecting discussions from previous meetings and including revised round 1 scenario submissions. Discuss modelling and scenario changes for Round 2.
round 2	*03-Jun-22*	***Distribute Round 2 Scenario Document & Data Template***	
	10-Jun-22	Round 2 Modelers Meeting	SC provide overview of R2 Scenarios & Data Template. Modeler Q&A w/SC and working group leads. Modeling teams will have the summer to complete round 2 model runs.
	02-Sep-22	***ROUND 2 OVERALL SCENARIOS DUE (Submmit to EMF 37 Database & if desired NCA 5 Database)***	
	16-Sep-22	Round 2 Overview Meeting	High level overview from round 2 results. Overview paper draft figures and outline.
	30-Sep-22	***ROUND 2 SG SCENARIOS DUE (Submmit to EMF 37 Database & if desired NCA 5 Database)***	
	14-Oct-22	Transportation and buildings deep dive	More detailed study group presentations. Study group papers draft figures and outlines.
	28-Oct-22	Industry and carbon management deep dive	
	04-Nov-22	*Round 2 revisions accepted for inclusion in results meeting*	
	11-Nov-22	Final Round 2 Results Meeting	Final results meeting. Draft Overview Paper Due.
	25-Nov-22	***FINAL DATA SUMBISSION FOR OVERVIEW PAPER & NCA 5***	

Table 7 presents the Round 2 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.

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 2. The remaining required Round 2 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).

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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 performance levels that technologies must meet. The storylines and specifications for these study group scenario assumptions are included in accompanying documents.

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.

Table 7
EMF 37 Round 2 Final Scenario Matrix

Short Scenario Name	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 Tech	Ref	Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R2	0by60.Ref.R2	0by80.Ref.R2	0GHGby50.Ref.R2
EMF All Adv	Adv	Adv	Adv	Adv	NT.All-Adv.R1	0by50.All-Adv.R2	0by60.All-Adv..R2	0by80.All-Adv.R2	0GHG0by50.All-Adv.R2
CMSG All Adv	Adv	Ref	Ref	Ref	NT.CMSG..Adv.R1	0by50.CMSG.Adv.R2			
TSG All Adv	Ref	Adv	Ref	Ref	NT.TSG.Adv.R1	0by50.TSG.Adv.R2			
ISG All Adv	Ref	Ref	Adv	Ref	NT.ISG.Adv.R1	0by50.ISG.Adv.R2			
BSG All Adv	Ref	Ref	Ref	Adv	NT.BSG.Adv.R1	0by50.BSG.Adv.R2			

Short Scenario Name	CMSG Scenarios: Technology: CCS	H2 Prod.	DAC	No Target	Net 0 by 2050	Net 0 by 2060	Net 0 by 2080
Ref Tech	Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R2	0by60.Ref.R2	0by80.Ref.R2
No CCS	None	Ref	None		0by50.CMSG.1.R2	0by60.CMSG.1.R2	0by80.CMSG.1.R2
Adv CCS	Adv	Ref	Ref		0by50.CMSG.2.R2	0by60.CMSG.2.R2	0by80.CMSG.2.R2
Adv H2	Ref	Adv	Ref		0by50.CMSG.3.R2	0by60.CMSG.3.R2	0by80.CMSG.3.R2
Adv DAC	Ref	Ref	Adv		0by50.CMSG.4.R2	0by60.CMSG.4.R2	0by80.CMSG.4.R2
CMSG All Adv	Adv	Adv	Adv	NT.CMSG.Adv.R1	0by50.CMSG.Adv.R2	0by60.CMSG..Adv.R2	0by80.CMSG.Adv.R2
No DAC	Ref	Ref	None		0by50.CMSG.6.R2	0by60.CMSG.6.R2	0by80.CMSG.6.R2
No New H2	Ref	No New	Ref		0by50.CMSG.7.R2	0by60.CMSG.7.R2	0by80.CMSG.7.R2

Short Scenario Name	Transportation: Technology: Adv. Tech	Policy: Policy Ambition	Preference: Behv. Chg.	No Target	Net 0 by 2050
Ref Tech	Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R2
TSG Tech	Adv	Cons	Cons		0by50.TSG.1.R2
TSG Policy	Cons	Adv	Cons		0by50.TSG.3.R2
TSG Preferences	Cons	Cons	Adv		0by50.TSG.4.R2
TSG Tech & Pol	Adv	Adv	Cons		0by50.TSG.2.R2
TSG All Adv	Adv	Adv	Adv	NT.TSG.Adv.R1	0by50.TSG.Adv.R2

Reference Scenario
Model Default Policy Scenario
All Advanced - Interaction Scenario
All Advanced - Study Group Scenario
Study Group Scenario
Optional Scenario

Short Scenario Name	Industry: Technology: EE	Mat. Eff.	RE/H2/CCUS	Ind. Elec	No Target	Net 0 by 2050
Ref Tech	Ref	Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R2
ISG EE	Adv	Ref	Ref	Ref		0by50.ISG.1.R2
ISG Mkt Eff	Ref	Adv	Ref	Ref		0by50.ISG.2.R2
ISG RE/H2/CCUS	Ref	Ref	Adv	Ref		0by50.ISG.3.R2
ISG Elec	Ref	Ref	Ref	Adv		0by50.ISG.4.R2
ISG All Adv	Adv	Adv	Adv	Adv	NT.ISG.Adv.R1	0by50.ISG.Adv.R2

Short Scenario Name	Buildings: Mrkt Bldg Tech Policy: Elec	EE	Standards Bldg Policy: Elec	EE	No Target	Net 0 by 2050
Ref Tech	Ref	Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R2
BSG Agg Elec	Adv	Ref	Adv	Ref		0by50.BSG.1.R2
BSG Mkt EEE	Adv	Adv	Ref	Ref		0by50.BSG.2.R2
BSG Stnd EEE	Ref	Ref	Adv	Adv		0by50.BSG.3.R2
BSG Mkt Elec	Adv	Ref	Ref	Ref		0by50.BSG.4.R2
BSG Stnd Elec	Ref	Ref	Adv	Ref		0by50.BSG.5.R2
BSG Agg EE	Ref	Adv	Ref	Adv		0by50.BSG.6.R2
BSG All Adv	Adv	Adv	Adv	Adv	NT.BSG.Adv.R1	0by50.BSG.Adv.R2

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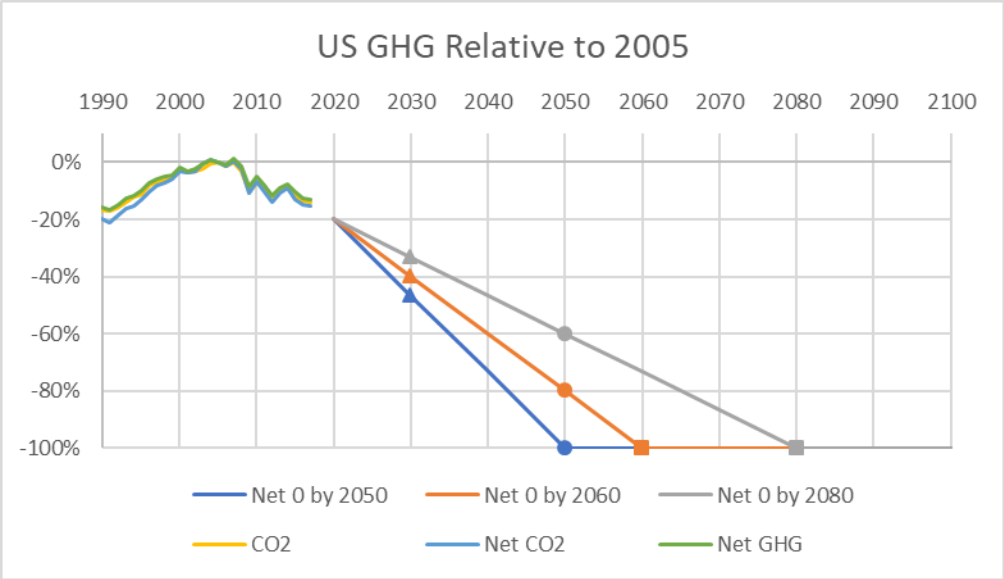


Figure 7. Illustrative decarbonization pathways for the US (Note: Canada and Mexico will follow similar straight-line reduction trajectories from 2020 to net zero.)

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 8.

A more detailed sectoral breakdown of the US GHG Inventory is presented in Table 9. 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

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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 8
US CO_2 emissions and LULUCF sink and assumptions (Mt CO_{2e})

	Inventory		*Projections / Targets*
Gas/Source	**2005**	**2018**	**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**

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Table 9

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.

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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.

4. OTHER RECENT LOW ENERGY SCENARIOS

Other Low energy Demand scenarios are nicely reviewed and comparer in IPCC, 2022 and IEA (2022), so will only be briefly summarized here. The Working Group 3 contribution to the IPCC's Sixth assessment report (IPCC, 2022) includes a set of illustrative Mitigation Pathways (IMPs), including a Low Demand IMP called IMP-LD which is of most interest here and significantly motivated by the Grubler. et al. (2018) scenario that was the starting point for the

IPCC AR6 Low Demand Scenario

The large number of global emissions scenarios assessed, including 1202 scenarios with projected global warming outcomes using climate emulators, come from a wide range of modelling approaches. They include the five illustrative scenarios (Shared Socioeconomic Pathways; SSPs) assessed by WG I for their climate outcomes but cover a wider and more varied set in terms of assumptions and modelled outcomes. For this assessment, Illustrative Mitigation Pathways (IMPs) were selected from this larger set to illustrate a range of different mitigation strategies that would be consistent with different warming levels. The IMPs illustrate pathways that achieve deep and rapid emissions reductions through different combinations of mitigation strategies. The IMPs are not intended to be comprehensive and do not address all possible themes in the underlying report. They differ in terms of their focus, for example, placing greater emphasis on renewables (IMP-Ren), deployment of carbon dioxide removal that result in net negative global GHG emissions (IMP-Neg) and efficient resource use as well as shifts in consumption patterns globally, leading to low demand for resources, while ensuring a high level of services and satisfying basic needs (IMP-LD) (Figure 10). Other IMPs illustrate the implications of a less rapid introduction of mitigation measures followed by a subsequent gradual strengthening (IMP-GS), and how shifting global pathways towards sustainable

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development, including by reducing inequality, can lead to mitigation (IMP-SP). The IMPs reach different climate goals as indicated in Table SPM.1 and Figure Box SPM.1 (IPCC, 2022).

All mitigation strategies face implementation challenges, including technology risks, scaling, and costs. Many challenges, such as dependence on CDR, pressure on land and biodiversity (e.g., bioenergy) and reliance on technologies with high upfront investments (e.g., nuclear), are significantly reduced in modelled pathways that assume using resources more efficiently (e.g., IMP-LD) or shift global development towards sustainability (e.g., IMP-SP) as illustrated in figure SPM-5 in the AR6 Summary for Policy Makers from Working Group 3 (IPCC, 2022) shown here:

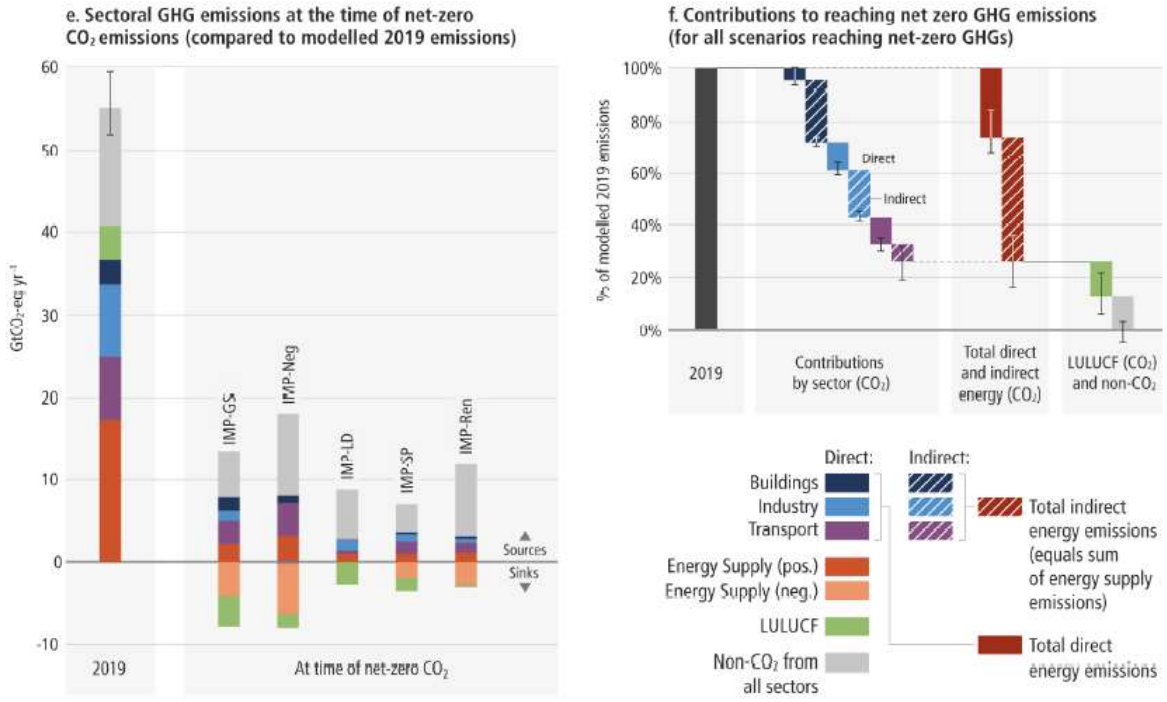


Figure 10. Illustrative Mitigation Emissions Pathways (IMPs) and net zero CO2 and GHG emissions strategies (Figure SPM 5 from IPCC, 2022)

Panel e shows the sectoral contributions of CO2 and non-CO2 emissions sources and sinks at the time when net zero CO2 emissions are reached in the IMPs. Positive and negative emissions for different IMPs are compared to the GHG emissions from the year 2019. Energy supply (neg.) includes BECCS and DACCS. DACCS features in only two of the five IMPs (IMP-REN, IMP-GS) and contributes <1 % and 64%, respectively, to the net negative emissions in Energy Supply (neg.).

Panel f shows the contribution of different sectors and sources to the emissions reductions from a 2019 baseline for reaching net zero GHG emissions. Bars denote the median emissions reductions for all pathways that reach net zero GHG emissions. The whiskers indicate the p5-p95

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range[5]. The contributions of the service sectors (transport, buildings, industry) are split into direct (demand-side) as well as indirect (supply-side) CO2 emissions reductions. Direct emissions represent demand-side emissions due to the fuel use in the respective demand sector. Indirect emissions represent upstream emissions due to industrial processes and energy conversion, transmission and distribution. In addition, the contributions from the LULUCF sector and reductions from non-CO_2 emissions sources (green and grey bars) are displayed.

IEA Annual Energy Outlook – 2022[6]

The Intergovernmental Panel on Climate Change (IPCC) published the first volume of its Sixth Assessment report in August 2021, after the IEA published its *Net Zero by 2050* report. The IPCC report confirms that rapid and deep reductions in CO2 emissions are necessary to limit warming to 1.5 °C (IPCC, 2021). In scenarios that achieve this objective with no or limited temperature overshoot, net emissions of greenhouse gases (GHGs) need to be reduced by 43% by 2030 compared with 2019 levels, and CO2 emissions need to reach net zero by around 2050 (IPCC, 2022a). The Glasgow Climate Pact which was adopted at COP26 reinforced the Paris Agreement objective of limiting warming to 1.5 °C by achieving net zero CO2 emissions by around mid-century as well as deep reductions in other GHGs.

In this context, this section presents a 2022 update to the IEA Net Zero Emissions by 2050 (NZE) Scenario. Its central purpose is still to reach net zero emissions from the energy sector by 2050, but this updated version considers the latest information about energy markets and technologies, and reflects concerns about energy security. The NZE Scenario is supported by new modelling using the climate model MAGICC which is widely used in the IPCC analyses and makes possible a richer assessment of the implications of the NZE Scenario for the global temperature.

The design approach for the updated NZE Scenario sticks closely to the approach followed in the IEA 2021 (IEA, 2021a) report:

- The NZE Scenario is based on the deployment of a wide portfolio of clean energy technologies, with decisions about deployment driven by costs, technology maturity, market conditions and policy preferences. The pathway reflects the particular circumstances of various countries in terms of resource and infrastructure endowments, development pathways and policy preferences.

- The NZE Scenario sees all countries contribute to the pathway to net zero emissions by 2050, with advanced economies taking the lead and reaching net zero emissions well

[5] Note these are 5th and 95th percentiles of the reported scenario results and not proabability distributions.
[6] This section draws heavily on and quotes freely from IEA (2022)

before emerging market and developing economies. Rapid transition is supported by global collaboration to facilitate ambitious policies, drive down the costs of clean energy technologies, create bigger and more international markets for those technologies, and support emerging market and developing economies to achieve emissions reductions and the energy-related United Nations Sustainable Development Goals (SDGs).

- The NZE Scenario aims to safeguard energy security through rapid deployment of clean energy technologies, energy efficiency and demand reduction while minimizing energy market volatility and stranded assets to the extent possible. It targets a smooth transition through strong and coordinated policies and incentives that enable all actors governments, investors, companies and workers – to anticipate the rapid change required.

The NZE Scenario is *a* pathway to reach net zero emissions by 2050, not *the* pathway. It sets out a comprehensive and detailed view of how the energy sector could respond coherently to the challenges of climate change while taking account of concerns about energy security and affordability.

The Updated IEA Net Zero Emissions Scenario

Between 2021 and 2030, CO2 emissions from the energy sector decrease by more than one third in the NZE Scenario, falling from 36.6 Gt today to less than 23 Gt in 2030.1 The electricity sector leads the way: emissions from electricity generation halve between 2021 and 2030, accounting for more than half of the overall emissions reductions from the energy sector. Growing electrification and the widespread deployment of efficiency and energy savings measures enable the buildings sector to almost halve its emissions by 2030. Rapid reductions are also seen in the transport sector, with emissions falling by one-quarter by 2030, thanks to electrification, efficiency improvements and behavioral change. The industry sector also sees a reduction of nearly a quarter by 2030 from 2021 levels, driven in particular by effective policies on materials efficiency, energy efficiency and fuel switching.

Between 2031 and 2040, the speed of emissions reductions in the industry and transport sectors accelerates to almost 10% per year, as electrification, low-emissions fuels, and carbon capture, utilization and storage (CCUS) technologies start to make bigger inroads into the existing stock of assets. The electricity sector reaches zero net emissions in advanced economies by 2035, and in emerging market and developing economies by 2040. The rapid drop in emissions in electricity helps to bring about continued reductions in emissions in the transport and buildings sectors as they electrify. By 2040, most of the remaining 5.8 Gt of energy sector emissions are from the transport sector (40% of the total, mainly from ships, planes and heavy trucks), and the industry sector (55%).

By 2050, all end-use sectors achieve emissions reductions of more than 90% compared to current levels, although residual CO_2 emissions are about 0.5 Gt in transport and 0.4 Gt in industry. These, and net residual emissions from other sectors, are counterbalanced by carbon dioxide removal (CDR) from the atmosphere through bioenergy with carbon capture and storage (BECCS) in electricity generation and biofuels production, and through direct air capture and storage (DACS). By 2050, CDR reaches 1.4 Gt per year (Figure 11).

In addition to rapid cuts in CO2, the NZE Scenario entails a steep fall in other energy-related GHGs. For example, energy-related methane emissions drop by 75% from 120 million tonnes (Mt) in 2021 to 30 Mt in 2030, on track for less than 10 Mt in 2050. There are also reductions in energy-related nitrogen dioxide emissions.

IEA modeling of land-use change and bioenergy production indicates that, taking account of the level of bioenergy production in the NZE Scenario and assuming parallel action to halt and reverse deforestation, CO2 emissions from agriculture, forestry and other land use (AFOLU) would drop to become a net CO2 sink before 2030.

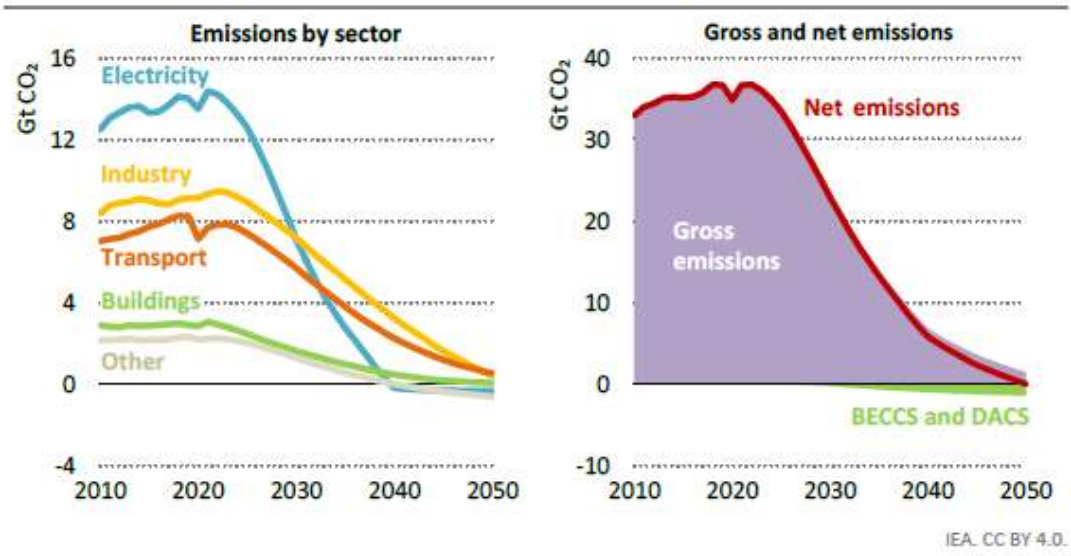
The steep reductions in GHG in the NZE Scenario would achieve the goal of the Paris Agreement to limit the long-term global temperature rise to "...well below 2 °C above pre-industrial levels ... pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels". The global temperature rise in the NZE Scenario peaks under 1.6 °C around 2040 before dropping to around 1.4 °C in 2100 (Figure 12). 2 In the Stated Policies Scenario (STEPS), by contrast, temperatures reach 2 °C around 2060, and continue to rise thereafter.

Due to uncertainties about the physical response of the climate to GHG emissions, it should be noted that such projections of future levels of warming are probabilistic in nature: for example, in the STEPS there is an 10% chance of a temperature rise above 3.2 °C in 2100. Such an increase would pose a severe threat to the wellbeing of humans and global ecosystems, with some of the starkest consequences manifesting themselves in the least wealthy parts of the world (IPCC, 2022b and IEA, 2022a).

Energy Trends

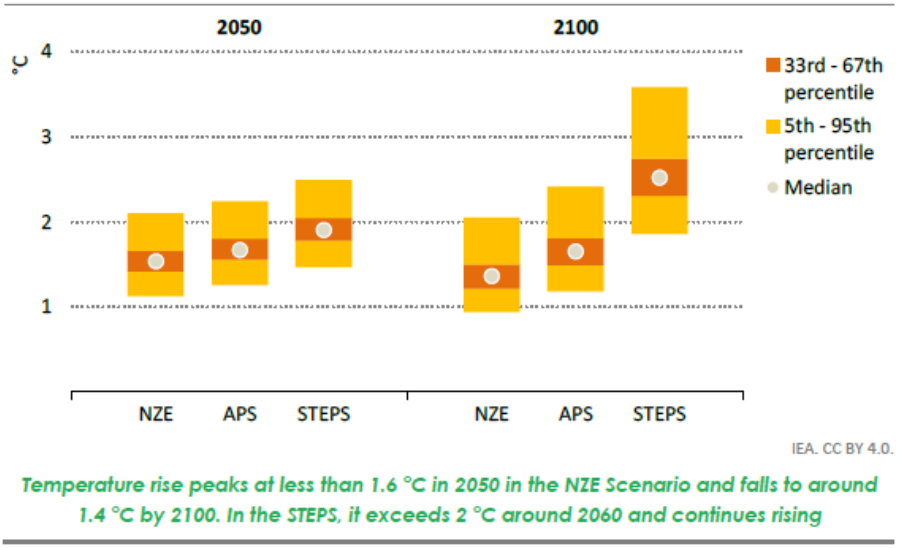
In the NZE Scenario, the global energy mix undergoes a profound transformation as low emissions sources ramp up dramatically and displace unabated sources across the whole energy sector. Between 2021 and 2030, low-emissions sources of supply increase by around 125 exajoules (EJ) (Figure 13). The traditional use of biomass is phased out as energy access goals are achieved. Among low-emissions sources, modern bioenergy and solar increase the most to 2030 by around 35 EJ and 28 EJ respectively.

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Notes: BECCS = bioenergy equipped with CCUS; DACS = direct air capture and storage. Other includes agriculture and other energy transformation sectors.

Figure 11. Energy-related CO2 emissions by sector and gross and net emissions in the NZE Scenario, 2010-2050 (Source: IEA, 2022g, p. 126)



Notes: NZE = Net Zero Emissions by 2050 Scenario; APS = Announced Pledges Scenario; STEPS = Stated Policies Scenario. Temperature rise estimates in this section are relative to 1850-1900 and match the IPCC Sixth Assessment Report definition of warming of 0.85 °C between 1995-2014 (IPCC, 2021).

Figure 12. Temperature rise in 2050 and 2100 in the *WEO-2022* scenarios (Source: IEA, 2022g, p. 127)

Thanks to electrification, improvements in energy efficiency and behavioral changes total energy supply declines by 10% between 2021 and 2030 even as the global economy grows by nearly a third. The annual rate of energy intensity improvement nearly triples as it rises to more than 4% per year. Unabated sources of supply decline by nearly a third, with unabated coal falling by nearly one-half and unabated natural gas by more than one-quarter by 2030. This contrasts with the NZE Scenario in the *World Energy Outlook 2021 (WEO-2021)*, in which natural gas held on to a larger share of the global energy mix for a little longer: the change reflects heightened energy security concerns around natural gas precipitated by Russia's invasion of Ukraine. Oil also declines by around one fifth to 2030 as a result of energy efficiency gains, behavioral change and increasing electrification in transport.

The transformation of energy supply is matched by a change in energy consumption (Figure 14). Total final consumption in 2021 amounted to around 440 EJ, an increase of 5.2% over the 2020 level. By 2030, total final consumption in the NZE Scenario is down by almost 10% on the 2021 level, despite rapid growth of global GDP. Over this period, the total final consumption intensity of GDP improves more than two-and-a-half- times faster than the average over the last decade. Four factors drive this improvement: efficiency benefits of switching from the traditional use of biomass; technical gains in energy consuming equipment and building envelopes; efficiency benefits of electrification; and behavioral change and avoided demand.

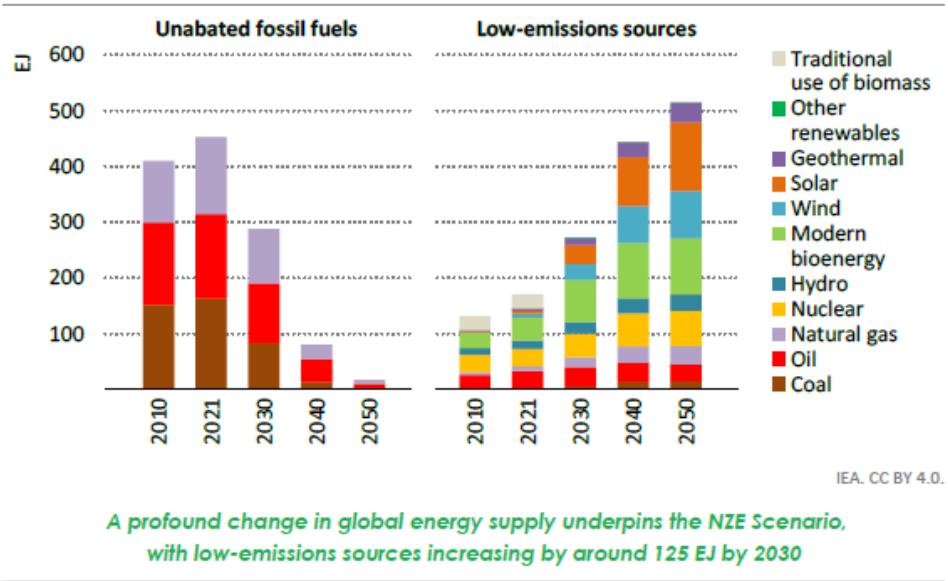


Figure 13. Total energy supply of unabated fossil fuels and low-emissions sources in the NZE Scenario, 2010-2050 (Source: IEA, 2022g, p. 128)

Unabated fossil fuels directly provided nearly 60% of total final consumption in 2021, excluding fossil fuel use for non-energy purposes such as chemical feedstocks. In the NZE Scenario, this falls to around 45% in 2030, and to only 5% by 2050. Electricity becomes the "new oil" in terms of its dominance of final consumption; unlike oil, however, it plays a key role in all end-use sectors. The share of electricity in total final consumption rises from 20% today to slightly less than 30% by 2030 and more than 50% by 2050. Hydrogen and hydrogen-based fuels take off after 2030 and account for 10% of total final consumption by 2050. In absolute terms, the consumption of bioenergy in end-use sectors remains broadly stable from today to 2050, rising from 46 EJ to slightly less than 50 EJ. However, this masks a shift in composition: the use of modern bioenergy rises sharply while the traditional use of bioenergy declines and then ends as full access to modern forms of energy is achieved in all countries by 2030.

Comparison With The New Scenarios Assessed By The IPCC

The third volume of the IPCC Sixth Assessment Report deals with climate mitigation (IPCC, 2022a). Published in April 2022, it includes a new scenario database (IIASA, 2022). Among the more than 1 000 scenarios vetted by the IPCC, only 16 achieved net zero emissions from the energy sector in 2050, and therefore are comparable in terms of energy sector

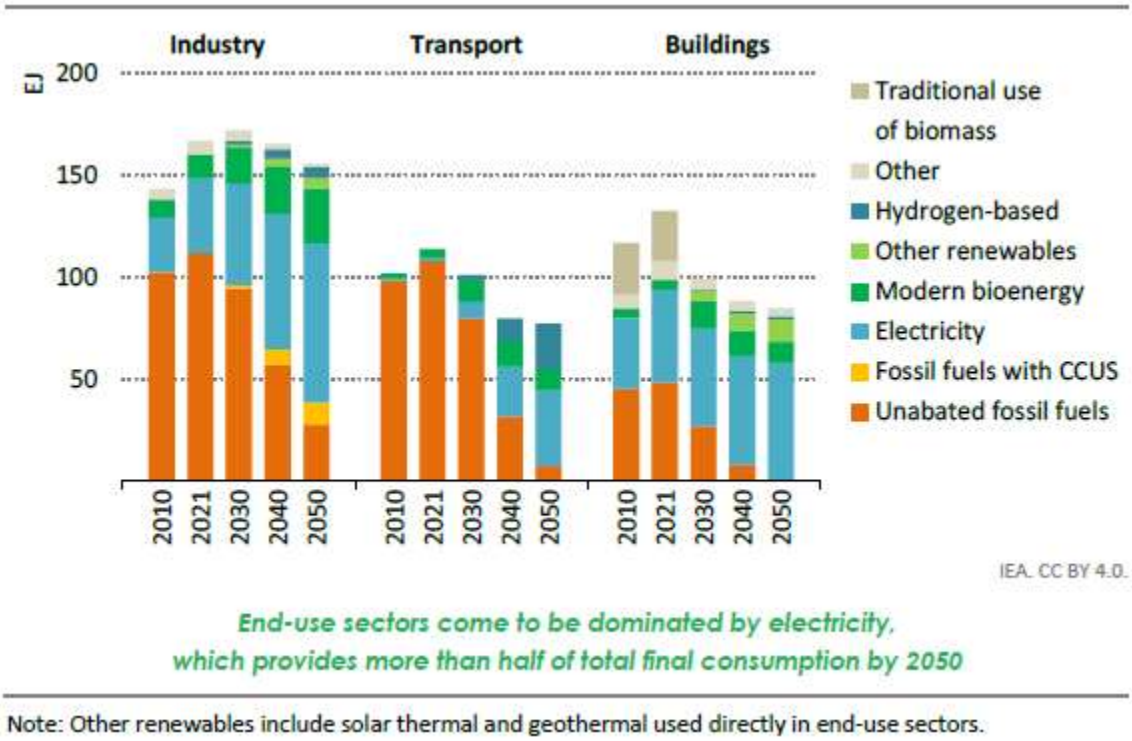


Figure 14. Total final consumption by source in the NZE Scenario, 2010-2050 (Source: IEA, 2022g, p. 129)

ambition with the IEA NZE Scenario. Here we highlight a comparison between those IPCC assessed scenarios and the IEA NZE Scenario (Figure 15).

- The IEA NZE Scenario entails very ambitious policies and measures to improve energy efficiency and reduce energy demand, including through behavioral change. As a consequence of this and the benefits of electrification, total final consumption is around 340 EJ in 2050, compared to around 460 EJ in the median IPCC scenario.

- The NZE Scenario sees the share of wind and solar in electricity generation reach. over 70% in 2050, compared to around 55% in the median IPCC scenario.

- The NZE Scenario sees total energy supply from bioenergy of around 100 EJ, reflecting the importance of remaining within identified sustainable limits for global bioenergy supply. The median IPCC scenario reaching net zero emissions by 2050 sees around 235 EJ of bioenergy demand, more than double the level of the NZE Scenario and three-and-a-half-times the current level.

- The NZE Scenario sees about 30 EJ of hydrogen and hydrogen-based fuels used to decarbonize end-use sectors that are difficult to electrify. The median IPCC scenario uses about 18 EJ of hydrogen and hydrogen-based fuels.

- The NZE Scenario uses 6.2 Gt of CCUS in 2050 while the median of the IPCC scenarios see about 17 Gt.

- The NZE Scenario relies on around 1.4 Gt of energy sector CDR from both BECCS and DACS, while the median IPCC scenario sees 12 Gt of energy sector CDR in 2050, largely from BECCS and mostly to offset continued use of oil in the transport sector.

Fuel Supplies

Oil, natural gas and coal accounted for around four-fifths of total energy supply worldwide in 2021. In the NZE Scenario, this share falls to around two-thirds in 2030 and less than one fifth in 2050, a proportion of which is used with CCUS and for non-energy uses. Between 2021 and 2050, coal demand declines by 90%, oil declines by around 80%, and natural gas declines by more than 70%.

Just under 100 EJ of fossil fuels are consumed in 2050 in the NZE Scenario. Just over 40% of this, including 65% of natural gas and 90% of coal, is consumed in facilities equipped with CCUS. A further 40% – including more than 70% of the oil still being used – is consumed in applications where the carbon is embodied in the product and there are no direct CO2 emissions (examples include chemical feedstocks, lubricants, paraffin waxes and asphalt).

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The remaining 20% is used in sectors where clean energy technologies are least feasible and cost effective: for example, oil still accounts for around 20% of fuel use in aviation in 2050 in

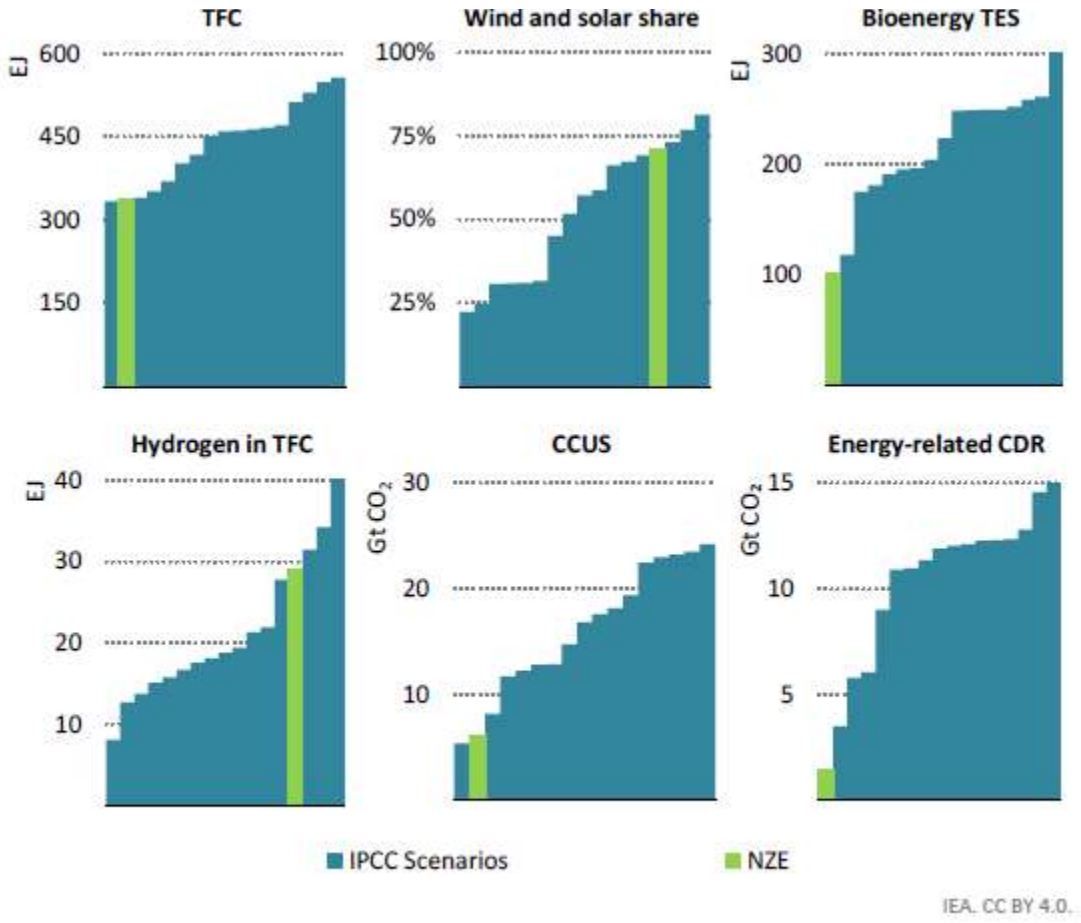


Figure 15. Comparison of key indicators for the selected IPCC scenarios and the IEA NZE Scenario in 2050 (Source: IEA, 2022g, p. 132)

the NZE Scenario. The unabated combustion of fossil fuels results in 1.2 Gt CO2 emissions in 2050, and these are fully offset by BECCS and DACS.

Coal use declines from 5 600 million tonnes of coal equivalent (Mtce) in 2021 to 3 000 Mtce in 2030 and to less than 600 Mtce in 2050 (Figure 16). Supply declines on average by more than 10% every year during the 2030s. Natural gas demand drops from around 4 200 bcm in 2021 to 3 300 bcm in 2030, and 1 200 bcm in 2050. Rates of decline are fastest in the 2030s, when natural gas use falls by 7% per year on average. Natural gas use

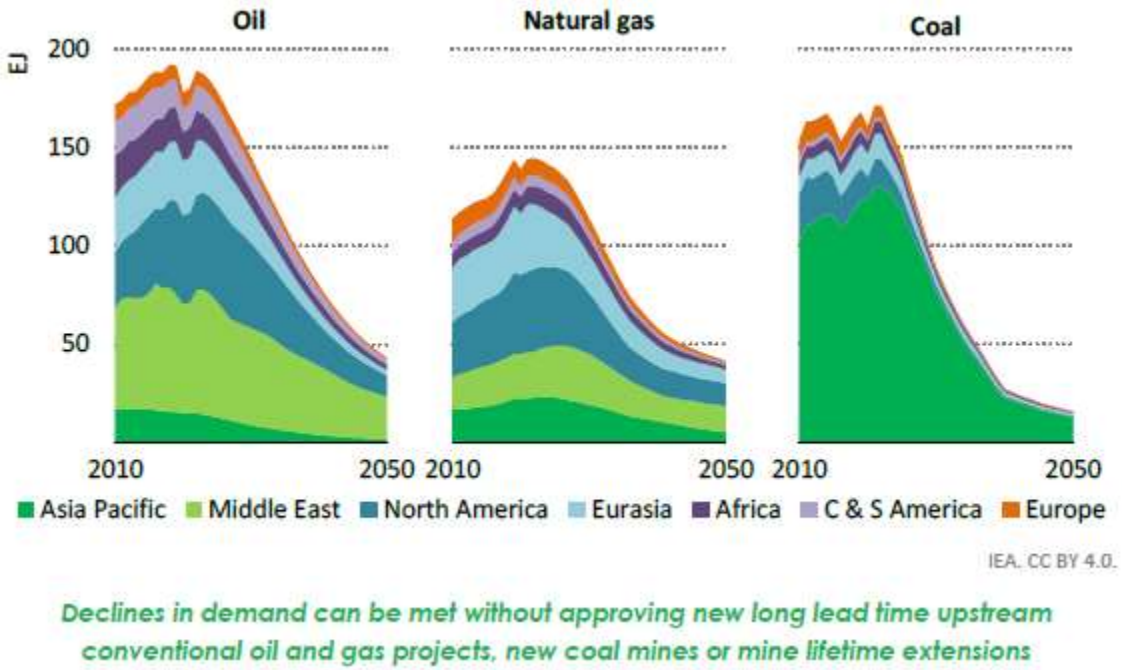


Figure 16. Oil, natural gas and coal supply by region in the NZE Scenario (Source: IEA, 2022g, p. 133)

continues to fall in the 2040s, but at a slower rate (around 3% per year) as reductions in gas use in power generation, industry and buildings are partly offset by increases in the volumes of gas being converted to low-emissions hydrogen. Oil demand declines from 95 million barrels per day (mb/d) in 2021 to 75 mb/d in 2030, and to less than 25 mb/d in 2050, with an annual decline rate of 6% on average from 2030 onwards.

The declines in fossil fuel demand in the NZE Scenario stem primarily from a major surge in clean energy investment (from around USD 1.2 trillion in recent years to USD 4.2 trillion in 2030). Some investment in existing supply projects continues in the NZE Scenario to ensure supply does not fall faster than the decline in demand. Other investment is undertaken to reduce the emissions intensity of remaining fossil fuel operations. In the NZE Scenario, this leads to a 50% reduction in the global average emissions intensity of oil and gas production between 2021 and 2030. If demand were to fall at the rates projected in the NZE Scenario, it could be met without approving the development of any new long lead-time upstream conventional oil and gas projects and without any new coal mines or coal mine lifetime extensions worldwide.

Reducing fossil fuel investment in advance of, or instead of, policy action and clean energy investment to reduce energy demand would not lead to the same outcomes as in the NZE Scenario. If supply were to transition faster than demand, with a drop in fossil fuel investment preceding a surge in clean energy technologies, this would lead to much higher

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prices – possibly for a prolonged period – even if the world moves towards net zero emissions. The scope for reductions in fossil fuel expenditure is closely linked to the scale and speed of increases in clean energy expenditure, and to the success of efforts to reduce energy demand: it does not make sense to look at any one of these factors in isolation from the others.

Russia's invasion of Ukraine adds an additional dimension to this analysis because it could lead to a substantial and prolonged reduction in Russian energy supplies. This is reflected in the updated NZE Scenario.

Turning first to oil, Russian production is lower in the 2022 NZE Scenario than it was in last year's NZE Scenario. The failure to ensure a sustainable recovery from the pandemic means that projected oil demand is at the same time higher in the mid-2020s in this NZE Scenario. The more suitable options to fill this combined gap are investments with shorter lead times and quicker payback periods, including extending production from existing fields and tight oil. The updated NZE Scenario also requires higher near-term production from members of OPEC than before to keep markets in balance, and a continuing high level of reliance on this production to meet remaining oil demand through to 2050. The share of oil supply coming from OPEC members rises from 35% in 2021 to 52% in 2050. Even though the oil market is much smaller in 2050 than today, the share of OPEC by then would be higher than at any point in the history of oil markets.

For natural gas, Russian production in the mid-2020s is lower than it was in the 2021 Net Zero Roadmap. However, in contrast to oil, near-term gas consumption has been revised downwards in this year's NZE Scenario as higher prices curb the cost effectiveness of gas helping to displace coal. Some new infrastructure may be needed to facilitate the diversification of supply away from Russia, and, with careful investment planning, there are opportunities for these to facilitate future imports of hydrogen or hydrogen-based fuels. Nonetheless, natural gas demand in the NZE Scenario can be met through continued investment in existing assets and already approved projects but without any new long lead time upstream conventional projects.

Low-emissions fuels

Net zero emissions does not mean the total phase out of fuels. Fossil fuel use declines, but there is rapid growth in low-emissions fuels (including solid, liquid and gaseous modern bioenergy, hydrogen and hydrogen-based fuels) (Figure 17). These play a key role in reducing emissions from long-distance transport and high-temperature industrial processes. In the NZE Scenario, low-emissions fuels comprise 20% of all liquid, solid and gaseous fuels used worldwide in 2030 and 65% by 2050.

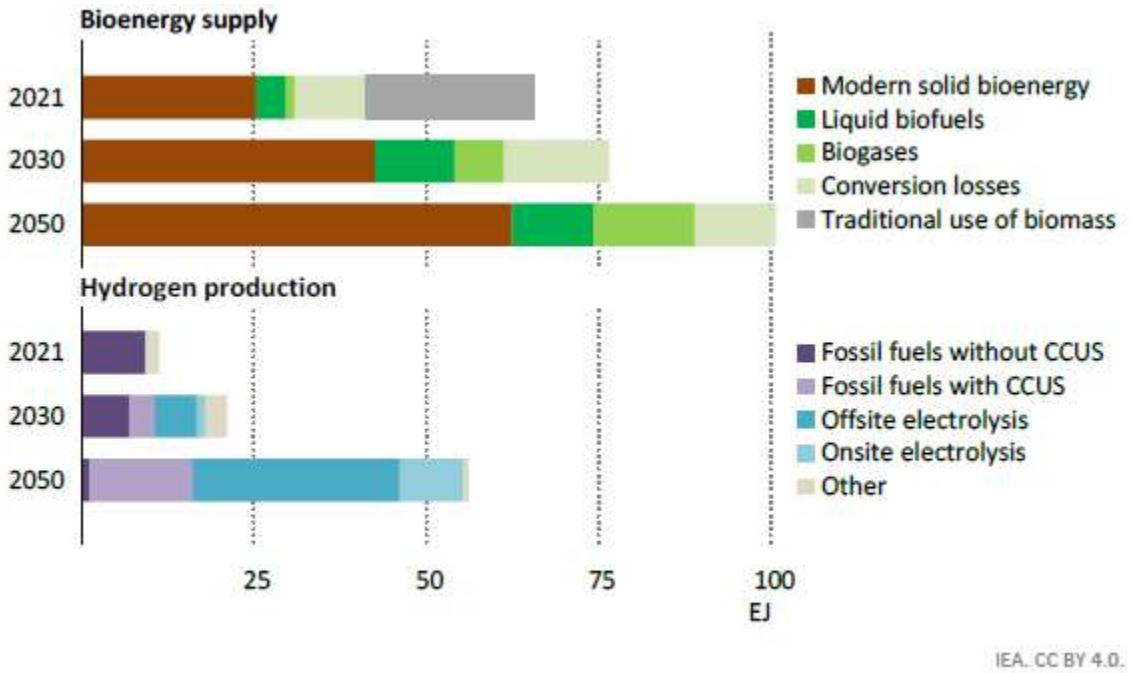


Figure 17. Bioenergy supply and hydrogen production by source in the NZE Scenario, 2021-2050 (Source: IEA, 2022g, p. 125)

For **bioenergy**, around 24 EJ of current consumption comes from the traditional use of biomass; this drops to zero as full access to modern cooking solutions is achieved by 2030 in the NZE Scenario. Modern bioenergy use increases from around 41 EJ today to more than 75 EJ in 2030 and to 100 EJ in 2050. In 2050, around one-third of this is used in the power sector, providing an important source of low-emissions dispatchable generation, and more than one-third is used in industry and buildings. Slightly less than 6 million barrels of oil equivalent per day (mboe/d) of liquid biofuels and 400 billion cubic meters equivalent of biogases are consumed in 2050. To avoid conflicts between food production and affordability, there is a general shift in the NZE Scenario away from conventional bioenergy sources towards advanced bioenergy, with around 50% of bioenergy supply coming from organic waste streams and forestry residues that do not require dedicated land use. Most of the remaining supply is provided by dedicated short rotation woody crops grown on cropland, pasture land and marginal lands that are not suited to food crops. There is no net increase in cropland use for bioenergy, and no bioenergy crops are grown on existing forested land in the NZE Scenario.

The supply of **low-emissions hydrogen** increases from 0.3 Mt (45 petajoules) today to 90 Mt in 2030 and 450 Mt in 2050.5 More than 95% of total hydrogen and hydrogen-based fuel use in 2050 is in transport, power and industry. Of the low-emissions hydrogen produced in 2050,

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a little less than three-quarters is produced via water electrolysis, and a bit more than one quarter is produced from fossil fuels with CCUS. The installed capacity of electrolyzers reaches 720 gigawatts (GW) in 2030 and 3 670 GW in 2050 (existing electrolyzer capacity is around 510 MW). In 2050, more than 14,800 TWh of electricity is used to produce low emissions hydrogen, equivalent to more than half of today's global electricity demand from all sources. Around 25% of total low-emissions hydrogen in 2050 is converted to low emissions hydrogen-based fuels. Synthetic kerosene produced from hydrogen (and combined with a non-fossil fuel source of CO_2) provides around 25% of energy use in the aviation sector, and ammonia and hydrogen provide more than 40% of energy use in shipping.

Electricity Generation

Global electricity generation increases over two-and-a-half-times in the NZE Scenario from 2021 to 2050. Total electricity generation increases by 3.2% per year to 2030 and then by 3.4% per year from 2030 to 2050, compared with 2.5% per year from 2010 to 2021. The electrification of end-uses ranging from EVs to space heating to industrial production raises the share electricity in final consumption from 20% in 2021 to almost 30% in 2030, and more than 50% in 2050. The rapid growth of low-emissions hydrogen adds almost 3 000 TWh of demand growth by 2030, and more than 14 800 TWh by 2050.

Low-emissions sources of electricity – renewables, nuclear power, fossil fuel power plants with CCUS, hydrogen and ammonia – expand rapidly in the NZE Scenario, overtaking unabated fossil fuels just after 2025 and reaching three-quarters of total generation by 2030, almost twice the share in 2021. Electricity sectors in advanced economies reach net zero emissions by 2035 in the NZE Scenario, and globally by 2040, at which point low-emissions sources provide nearly all electricity generation (Figure 18). This makes electricity the first energy sector to reach net zero emissions in the NZE Scenario, and that helps bring about emissions reductions in other sectors as they increasingly look to electricity to meet rising demand for energy services.

Renewables rapidly become the foundation of the global electricity sector in the NZE Scenario. The share of renewables in electricity generation rises from 28% in 2021 to over 60% in 2030, and nearly 90% in 2050. The total installed capacity of renewables triples to 2030 and rises sevenfold to 2050. Annual renewables capacity additions quadruple from 290 GW in 2021 to nearly 200 GW in 2030, and average above 1 050 GW from 2031 to 2050.

Solar PV and wind are the leading means of cutting electricity sector emissions: their global share of electricity generation increases from 10% in 2021 to 40% by 2030, and 70% by 2050 (Figure 19). Solar PV additions expand more than fourfold to 650 GW by 2030, and wind

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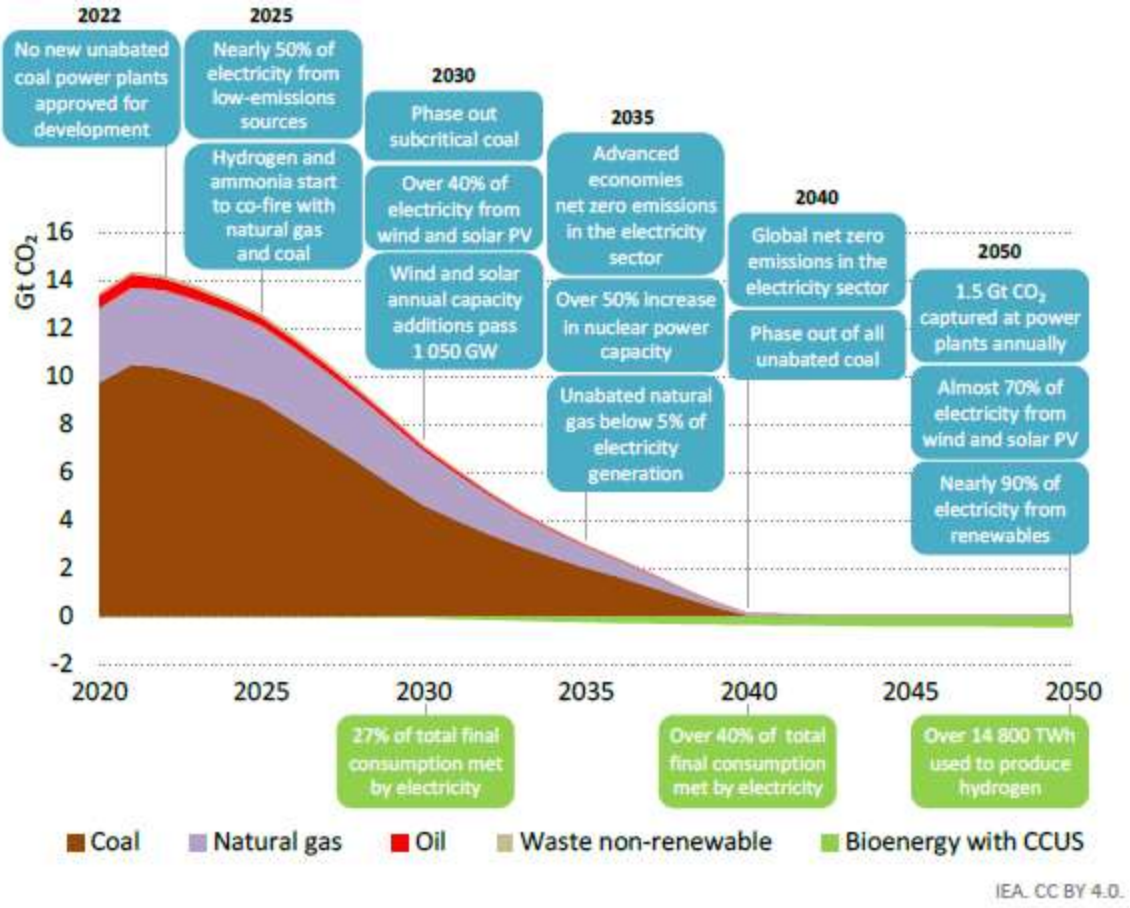


Figure 18. CO_2 emissions by source and key milestones in the electricity sector in the NZE Scenario, 2020 to 2050 (Source: IEA, 2022g, p. 137)

additions to over 400 GW, with more than 20% of this from the developing offshore wind industry. Capacity additions of hydropower and other dispatchable renewables triple by 2030 to over 125 GW, helping to cut emissions and providing low-emissions means of integrating the growing amounts of solar PV and wind.

Nuclear power generation more than doubles in the NZE Scenario by 2050, although its share falls from 10% in 2021 to 8% in 2050, as total generation expands rapidly. More than 30 countries, where nuclear power is accepted, increase their use of nuclear power. Widespread lifetime extensions in advanced economies provide a foundation. An annual average of 30 GW of new nuclear capacity comes online in the 2030s, marking a major comeback for the nuclear industry, and innovative technologies including small modular reactors become available on the market.

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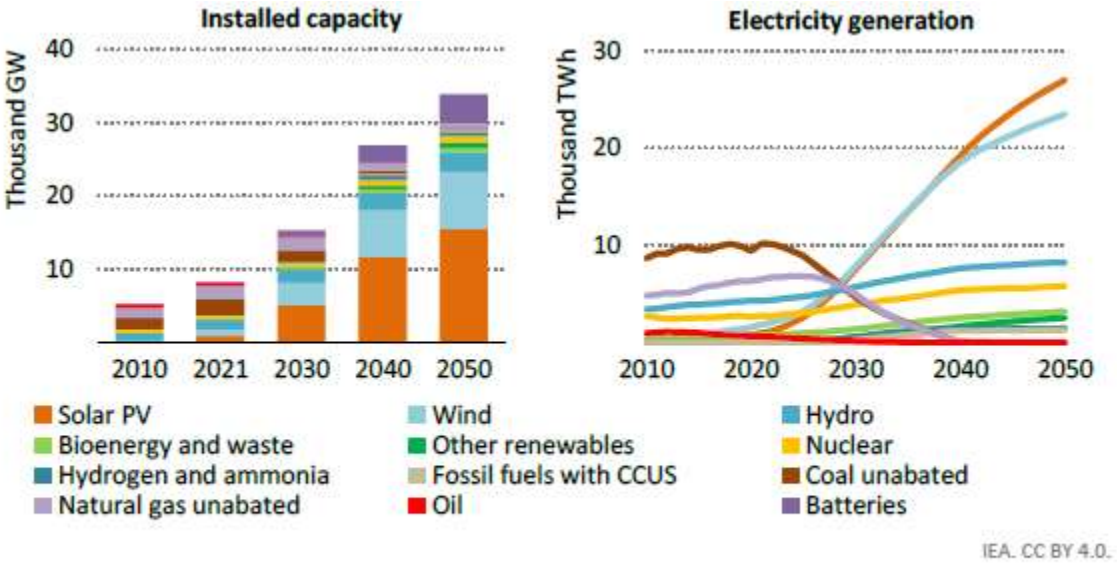


Figure 19. Total installed capacity and electricity generation by source in the NZE Scenario, 2010-2050 (Source IEA, 2022g, p. 138)

The use of low-emissions hydrogen and ammonia in natural gas- and coal-fired power plants and the addition of carbon capture technologies both provide important means of cutting emissions from existing power plants while supporting electricity security. The use of hydrogen and ammonia blended with natural gas and coal scales up in the late 2020s, and a total of 410 GW of natural gas-fired power plants and 160 GW of coal-fired plants are retrofitted by 2050 to co-fire ammonia and hydrogen, providing 2-3% of global electricity generation from 2030 to 2050. A total of over 60 GW of coal- and gas-fired power plants are retrofitted with CCUS by 2030, and this rises to over 330 GW by 2050. Fossil fuels with CCUS provide 1-2% of global electricity generation from 2030 to 2050.

Phasing out unabated use of coal to generate electricity is a central pillar of the NZE Scenario as coal is an emissions-intensive fossil fuel still in widespread use. Emissions from unabated coal were 9.7 Gt CO2 in 2021, accounting for 74% of the electricity sector total and 26% of total energy sector emissions. Despite a temporary boost from the current energy crisis as consumers switch from natural gas because of concerns about high prices and security of supply, the share of unabated coal in global electricity generation falls rapidly from 36% in 2021 to 12% in 2030, and to zero percent by 2040 and beyond. Low-emissions sources of generation grow so rapidly that no new unabated coal plants beyond those already under construction are built in the NZE Scenario.

Phasing out unabated coal emissions from power generation by 2040 worldwide depends on current power plants ceasing to provide regular baseload power. If the existing fleet of coalfired

power plants were to operate as they have in recent years, this alone would take up more than half of the remaining carbon budget consistent with limiting the global average temperature rise to 1.5 °C. However, such phasing out is not an easy proposition with an existing fleet of over 8 000 coal plants operating in some 90 countries and providing 2 million jobs. Against this background, it is important for there to be a range of options from which policy-makers can choose, which should include repurposing plants to focus on flexibility, retrofitting with carbon capture technologies, retrofitting to co-fire ammonia or biomass, and retiring them early.

Natural gas in the NZE Scenario faces a reduced role in this update compared with the 2021 version. This reflects current market conditions and changing perceptions of the affordability and security of natural gas. In this updated NZE Scenario, natural gas-fired generation peaks by 2025 before starting a long-term decline. By the time the global electricity sector reaches net zero emissions in 2040, the unabated use of natural gas is 97% lower than it was in 2021. Even as output falls, however, natural gas-fired capacity remains a critical source of power system flexibility in many markets, particularly to address seasonal flexibility needs.

Battery storage takes off in the NZE Scenario, expanding 30-fold from 2021 to 2030. This growth reflects its increasingly important role in helping to integrate rising shares of solar PV and wind by regularly charging at times of plentiful renewables supply and discharging when most needed in the system. Battery storage is also able to bolster the stability and reliability of electricity networks, for example by providing fast frequency response. By 2030, global battery capacity reaches 780 GW in the NZE Scenario and accounts for about 15% of all dispatchable power capacity. By 2035, battery capacity surpasses natural gas-fired capacity as the principal source of flexibility in many markets. Other forms of storage, such as heat or gravity-based systems, are under development and may emerge to complement or compete with battery storage.

Electricity transmission and distribution grids expand to meet the growing demands of electrification, connect thousands of new renewable energy projects, and reinforce systems that need to adapt to changing system dynamics. Global investment in grids to 2030 reaches close to USD 750 billion per year in the NZE Scenario, and it remains at a high level through to 2050. Close to 70% of this investment is for distribution grids with the aim of expanding, strengthening and digitalizing networks.

Electricity security is of paramount importance in the NZE Scenario as the global economy becomes more and more dependent on reliable and stable electricity supply. Security depends on grids being modernized and digitalized to facilitate more advanced and smarter operations as the number of users and uses of electricity expands and as the nature of electricity supply evolves. It also depends on system flexibility, which is fast becoming the

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cornerstone of electricity security. In the NZE Scenario, power system flexibility needs quadruple between today and 2050, driven by the fast-rising share of variable renewables and changes in electricity demand patterns. Unabated coal and natural gas power plants and hydro have traditionally provided the lion's share of flexibility to power systems. This changes dramatically in the NZE Scenario as electricity shifts to low-emissions sources of generation. Batteries and demand-side response meet more than half of the flexibility needs in 2050, with another quarter coming from hydropower and most of the rest from low emissions thermal power plants, including nuclear, fossil fuels equipped with CCUS and plants that co-fire hydrogen or ammonia. Around 5% is still provided by unabated natural gas.

The affordability of electricity is a critical concern for consumers and policy makers in energy transitions, and it will become more critical still as electricity comes to represent an ever larger share of final consumption and total energy bills. In absolute terms, global electricity supply costs – including generation, storage and grids - more than double from today's level to USD 4.7 trillion annually in 2050. However, this increase in supply costs is less than the growth in electricity demand over the same period. In the NZE Scenario, electricity costs come down from their current high levels as cost-effective solar PV and wind are scaled up, and total electricity supply costs per unit of electricity generation are broadly stable to 2030. By 2050, the average cost of electricity is 10% below the level in 2021.

Massive investment in renewables and other low-emissions sources means that electricity supply becomes more capital intensive. Capital recovery rises from about 40% of electricity supply costs today to almost 80% in 2050 in the NZE Scenario, while fuel costs fall from one third to just 5% in 2050. As a result, electricity system costs become more predictable and energy market volatility declines. Both advanced economies and emerging market and developing economies see lower electricity system costs by 2050. The costs of transitions in emerging market and developing economies are kept down by particularly low solar PV and wind costs, linked to lower technology costs and high quality solar resources in many countries.

Most relevant to our interests here are the energy demand measures explicitly included in the IEA NZE scenario.

Avoiding growth in energy demand

Overview of measures

The decarbonisation pathway in the NZE Scenario cannot be achieved without the rapid and large-scale adoption of measures that limit growth in energy demand. Absent such measures, deployment of clean energy sources would be outpaced by fast rising demand for energy services. Measures include energy efficiency, fuel switching (notably electrification) and behavioral changes, and together they cut demand by 110 EJ relative to the STEPS in 2030

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(Figure 20). They ensure that the energy intensity of GDP falls by 4% per year on average over the next eight years. Reductions in energy demand also play an important role in energy security and affordability.

In industry, around half of the reductions in energy use in 2030 are due to measures which avoid demand in the NZE Scenario compared to the STEPS, such as gains in materials efficiency. Most of the remaining reductions come from energy efficiency measures supported by a mixture of technical innovation, standards and regulations, including a systematic preference for best-in-class electric motors and other equipment, and digital energy management systems. There is also a role for changes in behavior by consumers to consume less and recycle more, thereby reducing demand for industrial products, especially primary steel and plastics.

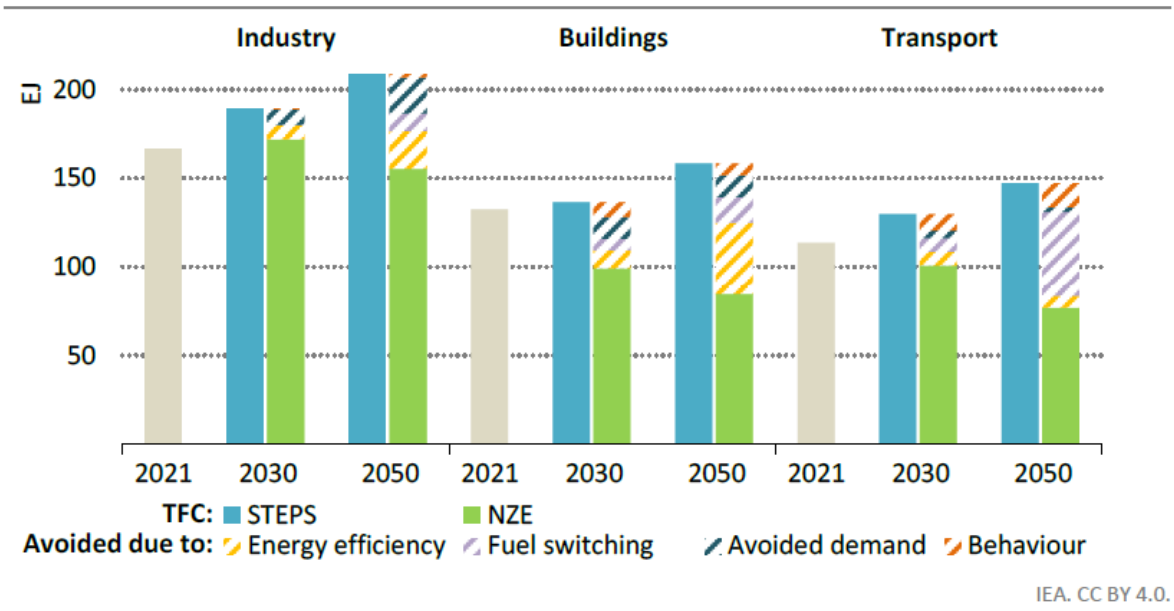


Figure 20. Total final consumption in the STEPS and demand avoided by measure in the NZE Scenario (Source: IEA, 2022g, p. 156).

In buildings, energy efficiency measures in the NZE Scenario avoid around one-quarter of the excess energy demand in the STEPS in 2030 and just over one-half of this in 2050. Fuel switching, largely from fossil fuel space heating to electric heat pumps, shaves a further onefifth from this energy demand gap. The remainder is avoided by behavioral changes that moderate demand, notably for space heating and air conditioning.

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transport, behavioral changes have a bigger impact than any other measure in 2030, accounting for one-third of the difference in energy demand between the STEPS and the NZE Scenario. These changes are particularly important in aviation, where there is little technical potential for fuel switching and limited room in the near term for energy efficiency gains beyond those in the STEPS. For road transport, fuel switching measures (mainly to EVs) and energy efficiency improvements underpinned by stringent fuel economy standards play an important role to curb growth in energy demand in 2030. But energy savings from electrification really come into their own after 2030, and there is a more than fourfold improvement in the average fuel economy of a car on the road in 2050 relative to today.

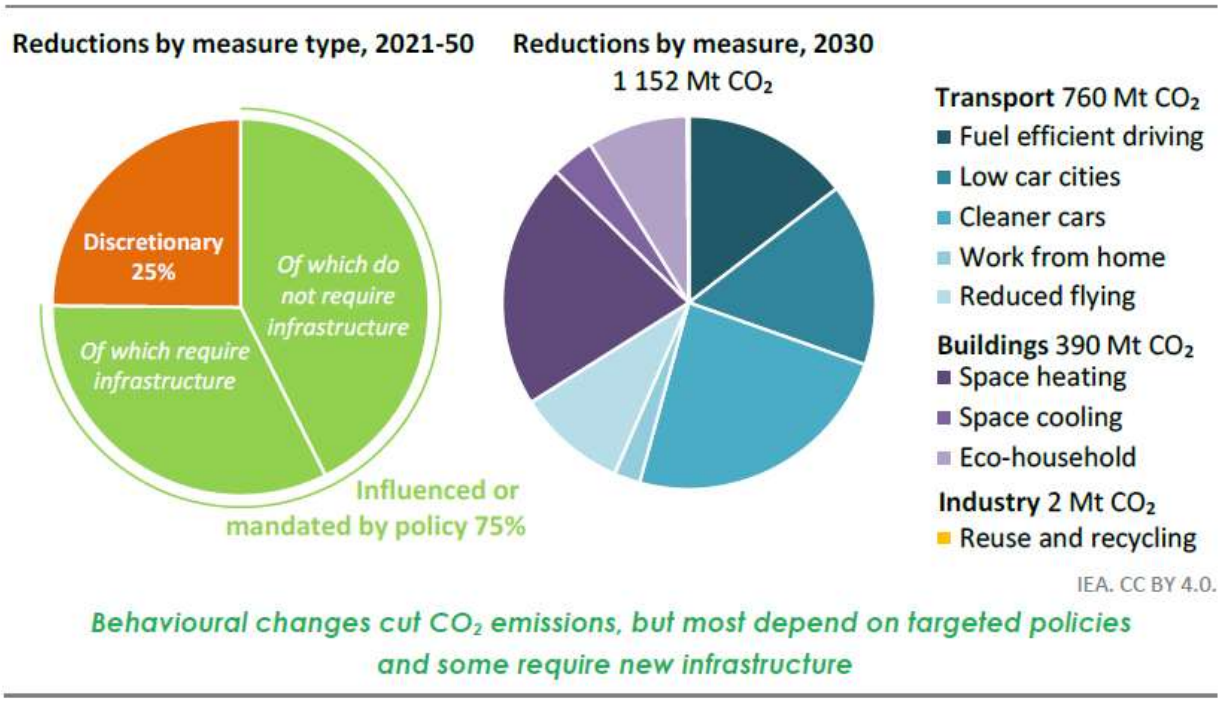
Focus on behavioral changes

The NZE Scenario incorporates a number of behavioral changes in the way consumers use energy services. In part these function in the same way as energy efficiency and other technical options to reduce energy demand. Yet there are also important distinctions.

- Behavioral changes can tackle emissions from the existing stock of emissions-intensive assets without the need to wait for stock turnover and the advance of clean energy technologies. For example, while over 60% of cars sold in the NZE Scenario are EVs in 2030, almost 80% of cars on the road are still ICE vehicles by that time and many of them will continue to be driven for years to come. By contrast, behavioral changes that lead people to drive less or in a more fuel-efficient manner, e.g. more slowly, cut emissions from all vehicles without any transitional period. For that reason behavioral changes can also provide rapid responses when necessary to energy security concerns (IEA, 2022b).
- In some areas such as aviation, technical options are unlikely to exist at the scale required to reduce emissions to net zero by 2050. Behavioral changes which curb activity therefore have a critical part to play in reducing demand and minimizing the need to rely on negative emissions technologies, which may be costly or fail to materialize at the requisite scale. In 2050, the behavioral changes in the NZE Scenario reduce the requirement for negative emissions technologies by around one-third, or 820 Mt CO2.

By 2030, behavioral changes in the NZE Scenario reduce CO2 emissions by around 1 150 Mt (or 9% of total emissions reductions) compared to levels in the STEPS (Figure 3.19). Between 2021-50 around three-quarters of cumulative emissions reductions from behavioral changes stem from measures directly shaped or mandated by government policies, such as congestion charging or speed limit reductions; around one-half of these require the support of infrastructure, such as high-speed rail networks. The remaining reductions are associated with discretionary behavioral changes which could be encouraged by information and awareness campaigns, such as product labelling and home energy consumption reports.

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[11] Behavioural changes are active changes by end-users of energy-related services that reduce excessive or wasteful energy consumption. This means, for example, that the purchase of clean energy technologies, such as an EV, is not considered as a behavioural change.

Figure 21. CO_2 emissions reductions due to behavioral changes in the NZE Scenario (source: IEA, 2022g, p. 157).

Buildings account for just over one-third of the total CO2 emissions reductions from behavioral changes in 2030. For example, adjusting thermostats to 19-20 °C in winter and air conditioning to a maximum of 24 °C in summer reduces CO2 emissions by almost 300 Mt (when including the indirect CO2 emissions associated with electricity generation and heat production).

Transport accounts for just under two-thirds of the reductions in CO2 emissions from behavioral changes in 2030 in the NZE Scenario. For road transport, measures to promote fuel-efficient driving, including reducing speed limits on motorways to 100 kilometers per hour (km/hour) and eco-driving,12 reduce CO2 emissions by 170 Mt in 2030. Other measures encourage working from home three days per week in jobs where it is possible to do so and increased carpooling. Action is taken to phase out the use of ICE cars in large city centers, and reduce speed limits to 20 km/hour to discourage car use and make it easier and more enjoyable to cycle or walk. A shift towards cleaner cars is brought about by corporate targets to end the use of ICE cars in commercial ride-hailing fleets, e.g. Uber, and by policies to discourage ownership of sport utility vehicles (SUV) including by banning their use in city centers.

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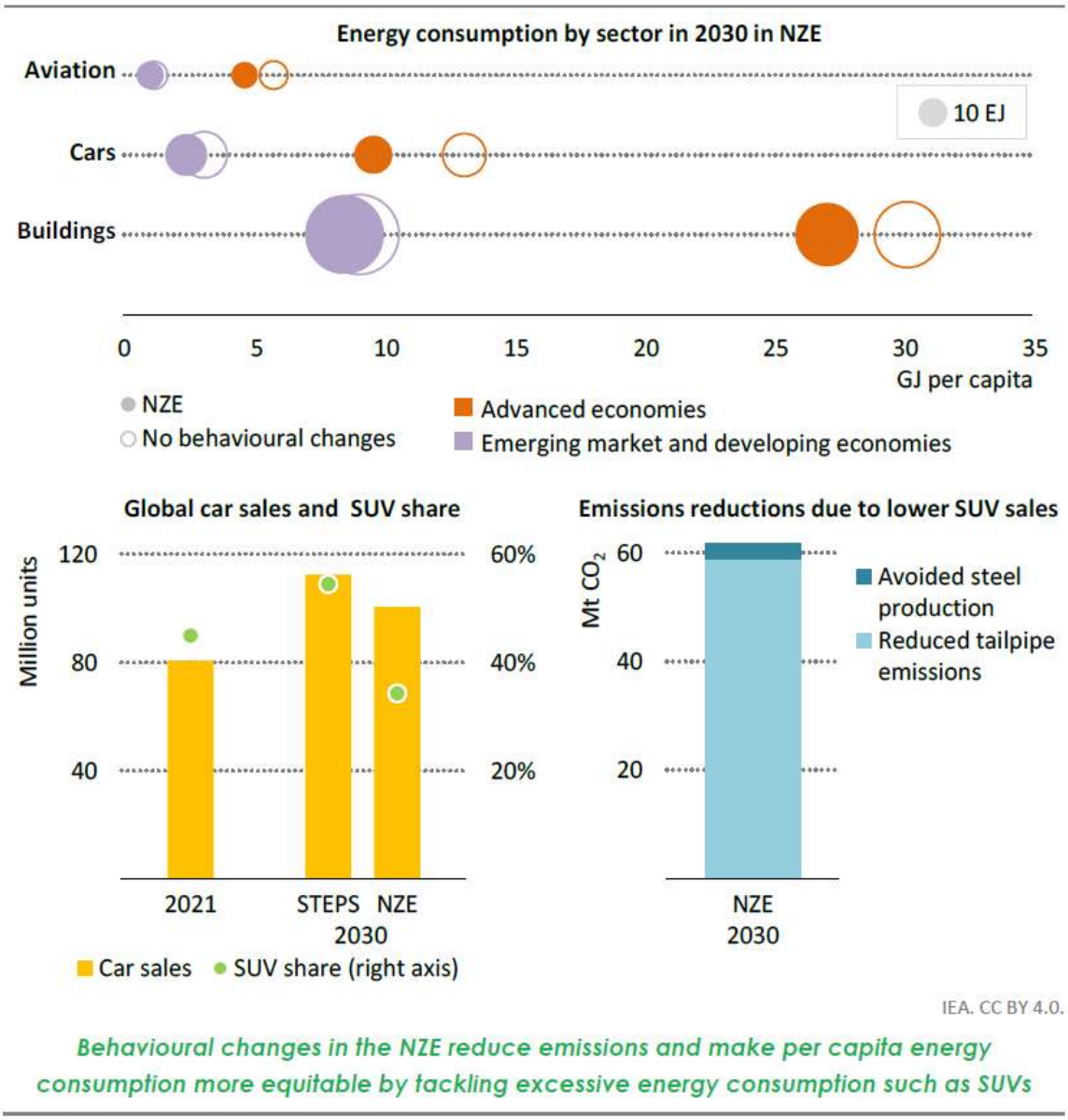
In aviation, a combination of frequent flyer levies, a 50% reduction in business-related long-haul trips in favor of teleconferencing and a shift to high-speed rail for regional flights cuts CO_2 emissions by 110 Mt in 2030 in the NZE Scenario relative to the level in STEPS.

Many of the behavioral changes in the NZE Scenario target wasteful or excessive energy consumption, predominantly in wealthier parts of the world. Their main purpose is to reduce emissions, but some also act to reduce global inequalities in per capita energy consumption and CO2 emissions, making the clean energy transition more equitable.
Policies that discourage car use in cities are one example. Such policies have an impact on private car ownership levels, particularly in wealthy households that own multiple cars.15 In the NZE Scenario, car sales are around one-quarter above 2021 levels in 2030, but are around 10% lower than in the STEPS in that year (Figure 22).

Policies that discourage ownership and use of SUVs is another example, and with a starker effect. Almost half of cars sold today are SUVs, and this rises to 55% in the STEPS by 2030. SUV ownership is highly concentrated: in 2021, almost five-times more SUVs were sold per capita in advanced economies than in emerging market and developing economies. In the NZE Scenario, the growing trend in SUV sales reverses and their market share falls to around 35% in 2030 and around 25% by 2050. Because SUVs are around one-quarter less fuel efficient than a standard car, the reduction in their popularity saves almost 60 Mt CO2 in 2030 in the NZE Scenario. About 95% of the savings are associated with reduced direct emissions (tailpipe), with the remainder from reduced emissions in industry due to a drop in demand for steel. The benefits of discouraging SUV sales remain even as car fleets electrify in the NZE Scenario, not least because a stronger preference for smaller and lighter vehicles reduces the need for critical minerals for batteries, easing the burden on supply chains as they scale up to meet rapidly increasing EV demand.

The behavioral changes in the NZE Scenario reflect regional differences in social norms and cultural values, as well as differences in geography, climate, urbanization and the ability of existing infrastructure to support the changes. However, the speed and scale of behavioral changes is arguably more uncertain than that which characterizes some other parts of the clean energy transition (for instance the deployment of solar PV, for which a clear trend has emerged in recent years). Consumer choices and habits often depend on trends that are hard to anticipate and can be subject to the influence of companies via marketing and advertising. In the NZE Scenario, governments introduce bold and consistent policies to encourage and make commercially viable those corporate strategies and business models
which divert consumer demand away from wasteful or high-emitting consumption towards sustainable and low-emissions energy-related goods and services, for example by mandating The Phasing Out Of Frequent Flyer Programs And Promoting The Implementation Of Similar schemes for rail travel. There would also be a role for policies to tackle activities linked to

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Note: GJ = gigajoule; SUV = sport utility vehicle.

Figure 22. Energy consumption per capita in the NZE Scenario and car sales and SUV share in the STEPS and NZE Scenario, 2030 (Source: IEA, 2022g, p. 161).

excessive and highly unequitable emissions, such as the use of private jets, which emit up to twenty-times more CO2 than an average commercial flight for every passenger-kilometer flown (Mumbower and Sobieralski, 2022; Gössling and Humpe, 2020).

5. CONCLUSIONS

This snapshot of the current status of the EDITS project, the EMF 37 study, and the IPCC and IEA reviews leads to a number of insights regarding progress made towards their objectives so far and **strategies** for achieving them more fully over the next year or two.

i. It Seems Clear That Not Enough Attention Has Been Given To Low Demand Scenarios and that the Edits Community has Led the Way in Highlighting the Potential Multiple Benefits of Such Scenarios

The influence of EDITs participants on the latest round of the IPCC has been significant and has led to some increase in the visibility or LD scenarios and the still limited number of LD scenarios in the IPCC data base doubtless inspired the Low Demand Illustrative Mitigation Pathway (IMP-LD), but it is only one of five IMGs and has a smaller number of scenarios in the IPCC data base associated with it. This is a situation which the work of the EDITS project can help remedy even before the next IPCC round gets underway. There needs to be a richer set of LD scenarios available to compare with the large number of different supply oriented net zero emissions scenarios now available.

ii. A Large Advantage the EDITs Project has Over Individuals or Individual Research Groups That Advocate for Much Greater and Holistic Emphasis on the Demand Side of Energy Systems Analyses in Developing Transition Pathways is its Open Science-Based Research Program Which Could be Strengthened Further in the Years Ahead

This would involve both further development of critical insights and numbers within the work of the current consortium members (allowing for some healthy disagreement about what would be feasible and desirable), but also seeking feedback and critical review by the more science oriented leaders of both the energy demand side skeptic and advocacy communities. This process could also help sharpen the messages produced by the consortium and help prepare the broader scientific community for consuming the products of The EDITs program as its communication strategy is implemented.

iii. 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 EMF 37 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 four individual study groups and seven cross-cut writing teams 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.

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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. This process has been supplemented by the direct research work of the sectoral study groups and cross cut writing teams

Similarly, the EDITs project has produced a study design and protocol that encourages the systems modeling teams to try to produce more forward looking low energy demand scenarios by including more aggressive energy demand targets and offering advice on ways to meet them. This has been supplemented by deep dives into the welfare metrics literature (with an emphasis on characterizing Decent Living Standards (DLSs), whereas EMF 37 has left the computation of a few of possible welfare metrics as a post model intercomparing exercise. EDITS also offers some more specific advice on modeling the rapid technology innovation of low energy demand enhancing technologies like formulating learning curves based on number of units in use rather than cumulation installed capacity, whereas EMF 37 allows the models to choose their own options for representing technological change we no models yet implementing the units is use learning paradigm. Moreover, EDITS has also included more detailed recommendations on how to reflect the potential of digital technologies in LED scenarios while EMF 37 has offered only a few specific instances where such technologies could be transformational.

Perhaps the biggest difference in the emphasis of the two studies is that the EMF 37 study is explicitly considering a broader set of technological, behavioral, and regulatory options for reducing energy demand, but is not nearly as deep on end use service demand reductions and the basic materials production efficiency improvements being recommended in the EDITS project.

iv. 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 in both studies, 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.

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v. **In Moving Forward, the Studies 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.

vi. **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**

Initial EM 37 Cross Cut Groups are: (1) the Electricity Sector, (2) Hydrogen Production, Transportation and Use, (4) Bio-Energy Technologies, (4) Income Distribution and Equity, (5) Ancillary Impacts on Air and Water Pollution, (6) International Trade Interactions of Domestic Policies, and (7) European Perspectives on North American Climate Policies. Additional Cross-Cut Teams that are being considered include: (1) Technology Costs and Market Dynamics, (2) Consumer Behavior, Policy and Regulatory Assumptions, (3) Impacts of non-Climate Driven Polices (those on air pollutants, water and land use), and (4) 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.

vii. **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 lessons learned about areas where all the models could use further improvement.

6. 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

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two major differences are in the foci and scope of the two studies are: (1) The EMF 37 study is addressing the high electrification and net zero GHG scenarios, and the interactions between them, and EDITS is focusing on low energy demand scenarios, which could have GHG benefits as well as other benefits like reductions in 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 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 levels 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 traditional energy and environmental research communities, who have 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

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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 significant 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., Arpaio 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. Pleasing in this raged, was the new decision of the new European Energy and Climate Modeling Forum (European Climate and Energy Modelling Forum – European Climate and Energy Modelling Forum (ecemf.eu) to run the EMF 37 scenarios with the global modeling capabilities in their consortium. In addition some cross EDITS/EMF 37 participation of individual modeling and expert teams has allowed for sharing of information and more advanced pans for running some coordinated scenarios across the two studies.

Appendix A

Scenarios for Deep Decarbonization of Manufacturing[7] (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

[7] 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[8] 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[9] 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

[8] It should be noted that within this sector there are some larger energy users; food processing and metal based durables being the most obvious.
[9] This term is being used in the broadest sense of the word.

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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

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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.

IS5: "All of the above" IS1-4 combined

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.

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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:

viii. **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.

ix. **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	**Gag-Elec**	Aggressive	Reference	*Maximum electrification if ignore EE*
BS3	**Gag-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	Studs-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	Studs-Elec	Standards	Reference	*What if standards are applied to enforce electrification and EE is ignored?*
BS8	Gag-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 (Gag-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

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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

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

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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.

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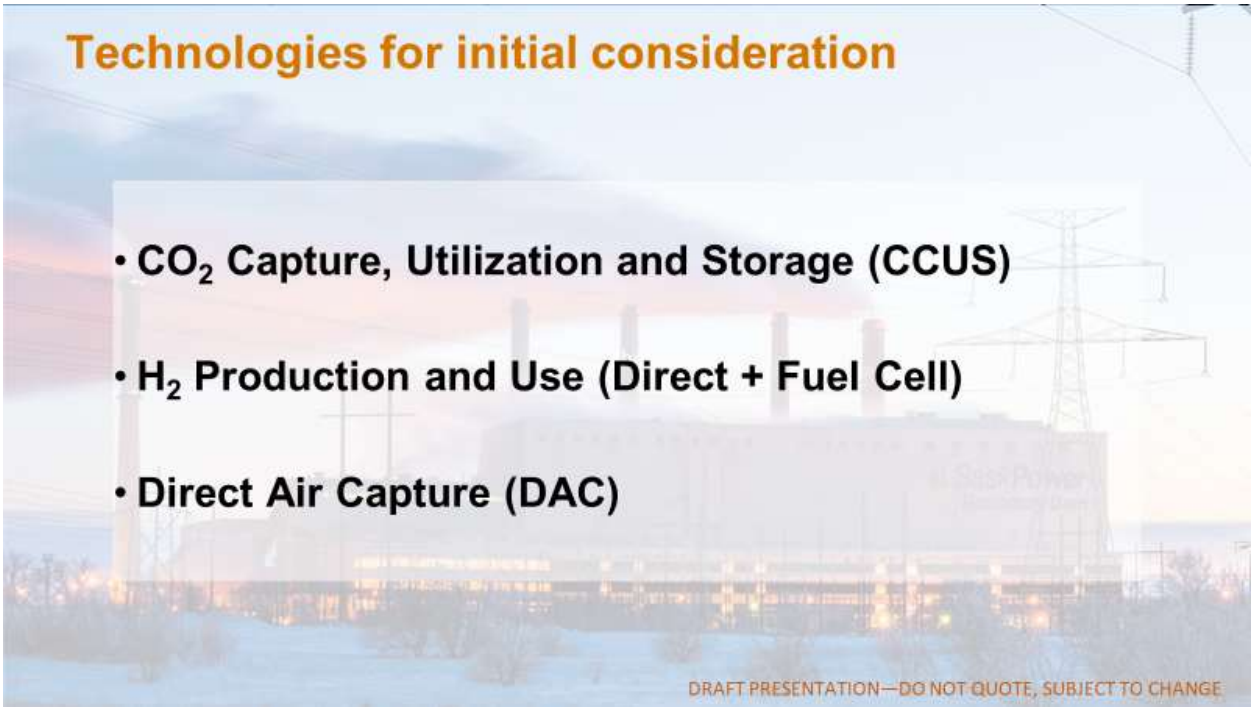
Scenario 8: Narrative for Model Implementation

- **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

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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	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-01-2060	CMSG-01-2080	Priority 2
CMSG-2	Adv	Ref	Ref		CMSG-02-2050	CMSG-02-2060	CMSG-02-2080	Priority 3
CMSG-3	Ref	Adv	Ref		CMSG-03-2050	CMSG-03-2060	CMSG-03-2080	Priority 4
CMSG-4	Ref	Ref	Adv		CMSG-04-2050	CMSG-04-2060	CMSG-04-2080	
CMSG-5	Adv	Adv	Adv		CMSG-05-2050	CMSG-05-2060	CMSG-05-2080	

1

Our 1st scenario is a core scenario, EMF37-01
- No Target
- BAU tech, pop, GDP

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CMSG Scenarios

EMF37 Core and Carbon Management Study Group (CMSG) Scenarios

	Technology							
Scenario ↓	CCS	H2 production and use	DAC	BAU	2050		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-01-2080	Priority 2
CMSG-2	Adv	Ref	Ref		CMSG-02-2050		CMSG-02-2080	Priority 3
CMSG-3	Ref	Adv	Ref		CMSG-03-2050		CMSG-03-2080	Priority 4
							CMSG-04-2080	
							CMSG-05-2080	

2

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

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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	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	CMSG-01-2080	Priority 2
CMSG-2	Adv	Ref	Ref		CMSG-02-2050	CMSG-		Priority 3
CMSG-3	Ref	Adv	Ref		CMSG-03-2050	CM	CMSG-03-2080	Priority 4
CMSG-4	Ref	Ref	Adv		CMSG-04-2050		CMSG-04-2080	
CMSG-5	Adv	Adv	Adv		CMSG-05	-05-2060	CMSG-05-2080	

Our focus is on learning in stages
Stage 1—solve for Ref + Net Zero 2080

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CMSG Met Friday 07 May 2021 to discuss progress and direction

EMF37 Core and Carbon Management Study Group (CMSG) Scenarios

	Technology				Net Zero Year			
Scenario ↓	CCS	H2 production and use	DAC	BAU	2050	2060	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	MSG-01-2060	CMSG-01-2080	Priority 2
CMSG-2	Adv	Ref	Ref			CMSG-02-2060	CMSG-02-2080	Priority 3
CMSG-3	Ref	Adv	Ref		MSG-03-2050	CMSG-03-2060	CMSG-03-2080	Priority 4
CMSG-4	Ref	Ref	Adv		MSG-04-2050	CMSG-04-2060	CMSG-04-2080	
CMSG-5	Adv	Adv	Adv	CM	CMSG-05-2050	CMSG-05-2060	CMSG-05-2080	

After our discussion last week, we discussed running 3 NetZero 2050 scenarios, if possible.

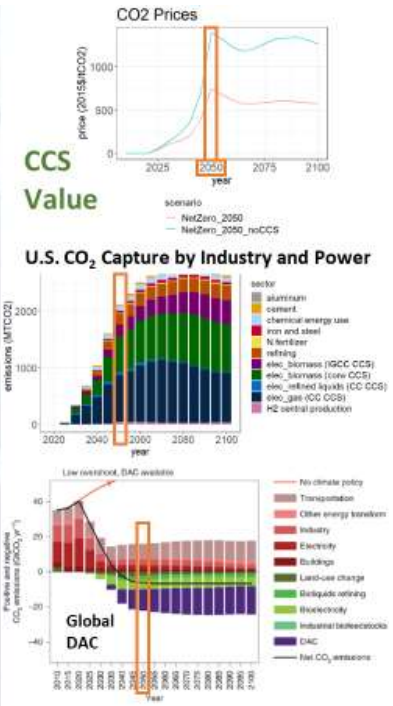
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Some key questions to answer

- **How does CCS affect the cost of emissions mitigation?**
- How much CO_2 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

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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

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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

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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

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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/tCO2

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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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Bibliography

Acquier, A., T. Daudigeos and J. Pinkse (2017). "Promises and paradoxes of the sharing economy: An organizing framework." Technological Forecasting and Social Change **125**: 1-10.

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

AlFaris, F., A. Juaidi and F. Manzano-Agugliaro (2017). "Intelligent homes' technologies to optimize the energy performance for the net zero energy home." Energy and Buildings **153**: 262-274.

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.

Arthur, B. W. (1989). "Competing Technologies, Increasing Returns, and Lock-In by Historical Events." The Economic Journal **99**(394): 116-131.

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.

Barnes, D. F., H. Samad and S. Rivas (2018). Meeting challenges, measuring progress: the benefits of sustainable energy access in Latin America and the Caribbean. Washington, DC, Inter-American Development Bank.

Bastia, T. and R. Skeldon (2020). Routledge handbook of migration and development, Routledge.

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

Bollinger, B. and K. Gillingham (2012). "Peer Effects in the Diffusion of Solar Photovoltaic Panels." Marketing Science **31**(6): 900-912.

Boserup, E. (1976). "Environment, population, and technology in primitive societies." Population and Development Review: 21-36.

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.

Brand-Correa, L. I. and J. K. Steinberger (2017). "A Framework for Decoupling Human Need Satisfaction From Energy Use." Ecological Economics **141**: 43-52.

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.

Brundtland, G. H. and M. Khalid (1987). Our common future, Oxford University Press, Oxford, GB.
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.

Catalini, C. and C. Tucker (2016). Seeding the S-curve? The role of early adopters in diffusion, National Bureau of Economic Research.

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

Costanza, R., B. Fisher, S. Ali, C. Beer, L. Bond, R. Boumans, N. L. Danigelis, J. Dickinson, C. Elliott and J. Farley (2007). "Quality of life: An approach integrating opportunities, human needs, and subjective wellbeing." Ecological economics **61**(2-3): 267-276.

Creutzig, F., M. Franzen, R. Moeckel, D. Heinrichs, K. Nagel, S. Nieland and H. Weisz (2019). "Leveraging digitalization for sustainability in urban transport." Global Sustainability **2**: e14.

Creutzig, F., J. Roy, P. Devine-Wright, J. Diaz-Jose, F. Geels, A. Grubler, N. Maizi, E. Masanet, Y. Mulugetta, C. D. Onyige-Ebeniro, P. E. Perkins, A. S. Pereira and E. U. Weber (2022). Demand, services and social aspects of mitigation. Climate Change 2022: Mitigation of Climate Change. Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). J. Skea and P. R. Shukla. Geneva, Switzerland, Intergovernmental Panel on Climate Change (IPCC).

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.

Di Giulio, A. and R. Defila (2019). "The ‘good life’ and Protected Needs." The Routledge handbook of global sustainability governance: 100-114.

Doblinger, C., M. Dowling and R. Helm (2016). "An institutional perspective of public policy and network effects in the renewable energy industry: enablers or disablers of entrepreneurial behavior and innovation?" Entrepreneurship & Regional Development **28**(1-2): 126-156.

Donner, J. and M. X. Escobari (2010). "A review of evidence on mobile use by micro and small enterprises in developing countries." Journal of International Development **22**(5): 641-658.

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.

Doyal, L. and I. Gough (1991). A theory of human need, Macmillan International Higher Education.

Dumitrescu, R., S. Groh, D. Philipp and C. von Hirschhausen (2020). Swarm Electrification: From Solar Home Systems to the National Grid and Back Again? Sustainable Energy Solutions for Remote Areas in the Tropics. O. Gandhi and D. Srinivasan. Cham, Springer International Publishing**:** 63-80.

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

Edelenbosch, O. Y., D. L. McCollum, H. Pettifor, C. Wilson and D. P. van Vuuren (2018). "Interactions between social learning and technological learning in electric vehicle futures."

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.

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.

Ehrlich PR, Holdren JP (1971). Impact of population growth. ObstetGynecol Surv 26(11):769. https ://doi.org/10.1097/00006 254-19711 1000-00014

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.

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 EMF24 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. *C*A.

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 Boehringer and Thomas Rutherford (Editors).

Energy Modeling Forum 37 (EMF, 2022). Revised EMF 37 Deep Decarbonization & High Electrification Scenarios for North America Study Description and Design *(Round. Version: R2.1,J.* McFarland, A Fawcett, T. Mai, G. Blanford, and J. Weyant, Energy Modeling Forum, Stanford University, Stanford, CA, June 10th.

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

Farmer, J. D., C. Hepburn, M. C. Ives, T. Hale, T. Wetzer, P. Mealy, R. Rafaty, S. Srivastav and R. Way (2019). "Sensitive intervention points in the post-carbon transition." Science **364**(6436): 132-134.

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.

Figueres, C. (2013). Innovation and technology for poverty eradication, International Institute for Communication and Development.

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

Fishman, T., N. Heeren, S. Pauliuk, P. Berrill, Q. Tu, P. Wolfram and E. 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 **n/a**(n/a).

Fletcher, J. M. and S. L. Ross (2018). "Estimating the effects of friends on health behaviors of adolescents." Health economics **27**(10): 1450-1483.

Fouquet, R. (2010). "The slow search for solutions: Lessons from historical energy transitions by sector and service." Energy Policy **38**: 6586-6596.

Fouquet, R. (2014). "Long-Run Demand for Energy Services: Income and Price Elasticities over Two Hundred Years." Review of Environmental Economics and Policy **8**(2): 186-207.

Frenken, K. (2017). "Political economies and environmental futures for the sharing economy." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences **375**(2095).

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.

Fuss, S., W. F. Lamb, M. W. Callaghan, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, W. de Oliveira Garcia, J. Hartmann, T. Khanna, G. Luderer, G. F. Nemet, J. Rogelj, P. Smith, J. L. V. Vicente, J. Wilcox, M. del Mar Zamora Dominguez and J. C. Minx (2018). "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters **13**(6): 063002.

Garnett, E. E., A. Balmford, C. Sandbrook, M. A. Pilling and T. M. Marteau (2019). "Impact of increasing vegetarian availability on meal selection and sales in cafeterias." Proceedings of the National Academy of Sciences **116**(42): 20923-2092

Gartner E, Sui T (2017) Alternative cement clinkers. Cem Concr Res. https ://doi.org/10.1016/j.cemco nres.2017.02.002

George, G., A. M. McGahan and J. Prabhu (2012). "Innovation for inclusive growth: Towards a theoretical framework and a research agenda." Journal of management studies **49**(4): 661-683.

Gillingham, K., M. J. Kotchen, D. S. Rapson and G. Wagner (2013). "Energy policy: The rebound effect is overplayed." Nature **493**(7433): 475-476.

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., C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D. McCollum, N. D. Rao, K. Riahi, J. Rogelj, S. D. Stercke, J. Cullen, S. Frank, O. Fricko, F. Guo, P. Havlik, M. Gidden, D.

Huppmann, G. Kiesewetter, P. Rafaj, W. Schoepp and H. Valin (2018). "A Low Energy Demand Scenario for Meeting the 1.5oC Target and Sustainable Development Goals without Negative Emission Technologies." Nature Energy **3**: 515-527.

Grubler, A., C. Wilson and G. Nemet (2016). "Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions." Energy Research & Social Science **22**: 18-25.

Grubler, A., G. Nemet, S. Pachauri, C. Wilson (2022). The 'High-with-Low' Scenario Narrative: Key Themes, Cross-Cutting Linkages, and Implications for Modelling, EDITS WG3 Narratives group *(Arnulf Grubler, Greg Nemet, Shonali Pachauri,* Charlie Wilson) Draft, 17 May.

Guadalupi, C. (2018). "Learning quality through prices and word-of-mouth communication." Journal of Economics & Management Strategy **27**(1): 53-70.

Haberl, H., D. Wiedenhofer, K.-H. Erb, C. Gorg and F. Krausmann (2017). "The Material Stock–Flow–Service Nexus: A New Approach for Tackling the Decoupling Conundrum." Sustainability **9**(7): 1049.

Hallegatte, S., M. Fay and E. B. Barbier (2018). "Poverty and climate change: introduction." Environment and Development Economics **23**(3): 217-233.

Hallegatte, S. and J. Rozenberg (2017). "Climate change through a poverty lens." Nature Climate Change **7**(4): 250-256.

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., and van 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.

Horner, N. C., A. Shehabi and I. L. Azevedo (2016). "Known unknowns: indirect energy effects of information and communication technology." Environmental Research Letters **11**(10): 103001.

Hossain, M. (2022). "Frugal entrepreneurship: Resource mobilization in resource-constrained environments." Creativity and Innovation Management.

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

International Energy Agency (2011). Harnessing variable renewables: a guide to the balancing challenge. Organization for Economic Co-operation and Development, Paris

IEA (International Energy Agency) (2016). World energy balances 2016. OECD Publishing, Paris. https ://doi.org/10.1787/9789264263 116-en

IEA (2017). Digitalization and Energy. Paris, France, International Energy Agency.

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 (2019) Japan solar PV auctions. https://www.iea.org/policies/6563-japan -solar -pv-auctions?country=Japan &region=Asia Pacific. Accessed 7 May 2020

IEA (2021). Energy Efficiency 2021 - Analysis. Paris, France, International Energy Agency.

IEA (2022). International Energy Outlook, International Energy Agency, Paris.

ITF (2017). Transition to Shared Mobility: How large cities can deliver inclusive transport services. Paris, France International Transport Forum (ITF).

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.

Jain, R. K., J. Qin and R. Rajagopal (2017). "Data-driven planning of distributed energy resources amidst socio-technical complexities." Nature Energy **2**: 17112.

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.

Kikstra, J. S., A. Mastrucci, J. Min, K. Riahi and N. D. Rao (2021). "Decent living gaps and energy needs around the world." Environmental Research Letters **16**(9): 095006.

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

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.

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.

Kloppenburg, S. and M. Boekelo (2019). "Digital platforms and the future of energy provisioning: Promises and perils for the next phase of the energy transition." Energy Research & Social Science **49**: 68-73.

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.

Komninos, N. (2019). Smart Cities and Connected Intelligence: Platforms, ecosystems and network effects, Routledge.

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.

Korcaj, L., U. J. Hahnel and H. Spada (2015). "Intentions to adopt photovoltaic systems depend on homeowners' expected personal gains and behavior of peers." Renewable Energy **75**: 407-415.

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

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

Kubli, M. and S. Ulli-Beer (2016). "Decentralization dynamics in energy systems: A generic simulation of network effects." Energy Research & Social Science **13**: 71-83.

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

Lange, S., J. Pohl and T. Santarius (2020). "Digitalization and energy consumption. Does ICT reduce energy demand?" Ecological Economics **176**: 106760.

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

Li, S., L. Tong, J. Xing and Y. Zhou (2017). "The market for electric vehicles: indirect network effects and policy design." Journal of the Association of Environmental and Resource Economists **4**(1): 89-133.

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

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

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

Ma, T., A. Grubler and Y. Nakamori (2009). "Modeling technology adoptions for sustainable development under increasing returns, uncertainty, and heterogeneous agents." European Journal of Operational Research **195**(1): 296-306.

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

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

Max-Neef, M. A. (1991). "Human scale development: conception, application and further reflections." McCollum, D. L., C. Wilson, M. Bevione, S. Carrara, O. Y. Edelenbosch, J. Emmerling, C. Guivarch, P. Karkatsoulis, I. Keppo, V. Krey, Z. Lin, E. O. Broin, L. Paroussos, H. Pettifor, K. Ramea, K. Riahi, F. Sano, B. S. Rodriguez and D. P. van Vuuren (2018). "Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles." Nature Energy **3**(8): 664-673.

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

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

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

Ministerial Council on Renewable Energy Hydrogen and Related Issues (2017).

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

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/

Moon, M. J. (2017). "Government-driven Sharing Economy: Lessons from the Sharing City Initiative of the Seoul Metropolitan Government." Journal of Developing Societies **33**(2): 223-243.

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

Morawczynski, O. and M. Pickens (2009). "Poor people using mobile financial services: observations on customer usage and impact from M-PESA."

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

Morstyn, T., N. Farrell, S. J. Darby and M. D. McCulloch (2018). "Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants." Nature Energy **3**(2): 94-101.

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

Ministerial Council on Renewable Energy Hydrogen and Related Issues (2017).

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

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

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

Nemet, G. and J. Greene (2022). "Innovation in low-energy demand and its implications for policy." Oxford Open Energy **1**.

Nemet, G. F. (2019). How solar energy became cheap: A model for low-carbon innovation, Routledge.

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. (1997). "Do real-output and real-wage measures capture reality? The history of lighting suggests not." The economics of new goods **58**: 29-66.

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.

Nussbaum, M. (2003). "Capabilities as fundamental entitlements: Sen and social justice." Feminist Economics **9**(2-3): 33-59.

Ockwell, D., A. Sagar and H. de Coninck (2015). "Collaborative research and development (R&D) for climate technology transfer and uptake in developing countries: towards a needs driven approach." Climatic Change **131**(3): 401-415.

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
O’Shaughnessy, E., G. Barbose, R. Wiser, S. Forrester and N. Darghouth (2021). "The impact of policies and business models on income equity in rooftop solar adoption." Nature Energy **6**(1): 84-91.

Palm, A. (2017). "Peer effects in residential solar photovoltaics adoption—A mixed methods study of Swedish users." Energy Research & Social Science **26**: 1-10.

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.

Pearce, D.W. (1996). The MIT Dictionary of Modern Economics, 4th Edition. MIT Press, Cambridge, MA.

Peck, S.C. and T. J. Teisberg (1999). "CO2 Emissions Control Agreements: Incentives for Regional Participation, " Working Paper, EPRI.

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

Poblete-Cazenave, M., S. Pachauri, E. Byers, A. Mastrucci and B. van Ruijven (2021). "Global scenarios of household access to modern energy services under climate mitigation policy." Nature Energy **6**(8): 824-833.

Portney, P.R. and J.P. Weyant (1999). Discounting and Intergenerational Equity, Resources for the Future, Washington , D . C .

Power Generation Cost Verification Working Group of Advisory Committee for Natural Resources and Energy Nuclear power (2020). (In Japanese)

Prahalad, C. K., C. K. Prahalad, H. C. Fruehauf and K. Prahalad (2005). The Fortune at the Bottom of the Pyramid, Wharton School Pub.

Qiu, Y., S. Yin and Y. D. Wang (2016). "Peer effects and voluntary green building certification." Sustainability **8**(7): 632.

Rai, V. and S. A. Robinson (2013). "Effective information channels for reducing costs of environmentally friendly technologies: evidence from residential PV markets." Environmental Research Letters **8**(1): 014044.

Rai, V. and S. A. Robinson (2015). "Agent-based modeling of energy technology adoption: Empirical integration of social, behavioral, economic, and environmental factors." Environmental Modelling & Software **70**: 163-177.

Rao, N. D. and P. Baer (2012). " “Decent Living” Emissions: A Conceptual Framework." Sustainability Science **4**: 656-681.

Rao, N. D. and J. Min (2017). "Decent living standards: Material prerequisites for human wellbeing." Social Indicators Research.

Rao, N. D. and C. Wilson (2022). "Advancing energy and well-being research." Nature Sustainability **5**(2): 98-103.

Rawls, J. (1971). A theory of justice. Cambridge, MA, Harvard University Press.

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.

Rockstrom, J., W. Steffen, K. Noone, A. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen and J. A. Foley (2009). "A safe operating space for humanity." Nature **461**(7263): 472-475.

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Seferian and M. V. Vilarino (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. Global warming of 1.5°C: An IPCC Special Report. V. Masson-Delmotte, P. Zhai, H. O. Portner et al. Geneva, Switzerland, World Meteorological Organization**:** 93-174.

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

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

Scott, K., C. J. Smith, J. A. Lowe and L. G. Carreras (2022). "Demand vs supply-side approaches to mitigation: What final energy demand assumptions are made to meet 1.5 and 2 °C targets?" Global Environmental Change **72**: 102448.

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

SEforALL (2017). Why Wait? Seizing the Energy Access Dividend. Washington DC, Sustainable Energy for All, and Power for All.

Semieniuk, G., L. Taylor, A. Rezai and D. K. Foley (2021). "Plausible energy demand patterns in a growing global economy with climate policy." Nature Climate Change **11**(4): 313-318.
Sharma, G. and P. Sturges (2007). "Using ICT to Help the Poor Access Public Services: an action research programme." Information Development **23**(1): 15-24.

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.

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

Smith, A. (2005). "The alternative technology movement: an analysis of its framing and negotiation of technology development." Human Ecology Review **12**(2): 106.

Spencer T, Coauthors (2015). Beyond the Numbers: Understanding the Transformation Induced by INDCs

Stern, D. I. (2020). "How large is the economy-wide rebound effect?" Energy Policy **147**: 111870.

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.

Sweerts, B., R. J. Detz and B. van der Zwaan (2020). "Evaluating the Role of Unit Size in Learning-by-Doing of Energy Technologies." Joule **4**(5): 967-970.

The Japan Atomic Energy Relations Organization (2019). The results of a public opinion survey on nuclear energy (In Japanese)

Thompson, A. W. and Y. Perez (2020). "Vehicle-to-Everything (V2X) energy services, value streams, and regulatory policy implications." Energy Policy **137**: 111136.

Tong, D., Q. Zhang, Y. Zheng, K. Caldeira, C. Shearer, C. Hong, Y. Qin and S. J. Davis (2019). "Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target." Nature **572**(7769): 373-377.

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 (2020). Report of the UN Economist Network for the UN 75th Anniversary Shaping the Trends of Our Time. New York, United Nations.

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.

WBGU (2019). Towards our common digital future. Berlin, Germany, German Advisory Council on Global Change (WBGU).

WEF (2019). A New Circular Vision for Electronics: Time for a Global Reboot. Geneva, Switzerland, World Economy Forum (WEF) and Platform for Accelerating the Circular Economy (PACE).

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 .

Wilson, C., A. Grubler, N. Bento, S. Healey, S. De Stercke and C. Zimm (2020). "Granular technologies to accelerate decarbonization." Science **368**(6486): 36-39.

Wilson, C., T. Hargreaves and R. Hauxwell-Baldwin (2017). "Benefits and risks of smart home technologies." Energy Policy **103**: 72-83.

Wilson, C., L. Kerr, F. Sprei, E. Vrain and M. Wilson (2020). "Potential climate benefits of digital consumer innovations." Annual Review of Environment and Resources **45**: 113-144.

Wolske, K. S., K. T. Gillingham and P. W. Schultz (2020). "Peer influence on household energy behaviours." Nature Energy.

World Bank (2005). World Development Report 2006: Equity and Development. Washington, DC, World Bank.

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

Zhuge, C., M. Yu, C. Wang, Y. Cui and Y. Liu (2020). "An agent-based spatiotemporal integrated approach to simulating in-home water and related energy use behaviour: A test case of Beijing, China." Science of The Total Environment **708**: 135086.

2022年度 EDITSプロジェクト報告書

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

大阪大学は今年度，EDITSの活動として次の研究を実施した．

1) Annual meeting，Quarterly meetingへの参加
全ての定期ミーティングに参加し，発表の機会がある場合は発表を行った．

2) Buildingsグループにおけるレビュー論文作成
Modelling Socio-Behavioural，Technological，and Infrastructural Innovations for Low Energy Demand in Buildings---Current State and Research Needsをタイトルとする共著論文をAnnual Review of Environment and Resources誌に投稿した．

3) 東京大学杉山先生が主導しているEDITS model complementarity exerciseに参加し，大阪大学が開発している日本のエネルギー需要モデルの推計結果を提供した．

4) 民生部門を対象として，日本版Low Energy Demand（LED）シナリオ，High with Low（HwL）シナリオの開発を検討した．この一環として，IPCCの第6次報告書をレビューし，LEDシナリオ，HwLシナリオの分析枠組みを開発した．

本報告書では，3)，4)の内容を報告する．２章ではEDITS model complementarity exerciseの一環として実施した大阪大学による2050年の家庭部門エネルギー需要推計結果とLEDシナリオとの比較を示す．３章ではIPCC第6次報告書のBuildings，Sufficiencyに関する章でまとめられている知見を整理した結果を報告する．４章では，日本版LEDシナリオ，HwLシナリオの開発に向けて作成した枠組みを説明する．

２．大阪大学による2050年の家庭部門エネルギー需要推計結果とLEDシナリオとの比較

Low energy demand（LED）シナリオ[1)]は，世界が1.5℃目標の達成をネガティブエミッション技術に頼ることなく実現できることを示した．その中では，世界の国々をGlobal North（主に北半球に分布する先進国）とGlobal South（主に南半球に分布する途上国）に分類し，社会変化の傾向や十分に文化的な生活を送るための水準（decent living standard）を反映して将来のエネルギー需要を推計している．Global NorthとGlobal Southそれぞれについてエネルギーサービス需要や機器のエネルギー消費（効率）が想定されているが，国・地域ごとにエネルギー消費における諸条件が異なるため，具体的な分析のためには個別にLEDシナリオが示すような変化を検討する必要がある．このような背景から，本節では，大阪大学下田研究室が開発している家庭用エ

ネルギーエンドユースモデル[2]（Total Residential Energy End-use Simulation （TREES）モデル）を用いて，日本の家庭部門のエネルギー需要を推計するとともに，2050 年の推計結果を LED シナリオの値(Global North)と比較する.本内容の結果を EDITS model complementarity exercise に提供した.

２．１　家庭部門のエネルギー需要の推計方法

2020 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，概要のみを説明する．家庭部門のエネルギー需要推計には既報[2)~15)]のモデル，Total Residential End-use Energy Simulation (TREES) モデルを用いた（図 1)．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.

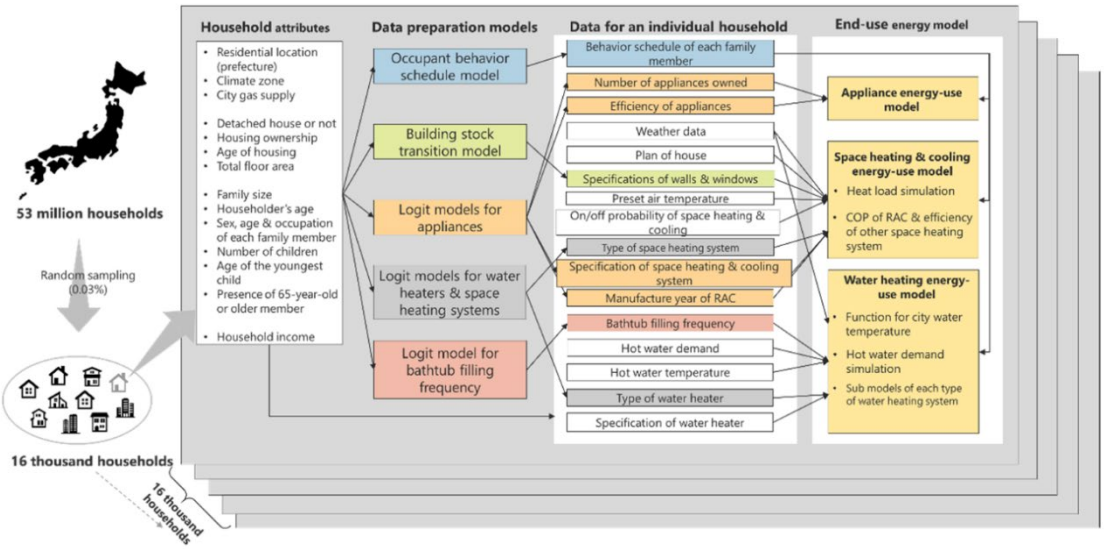


図 1　TREES モデルの概要[2)]

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　TREES における 2050 年のエネルギー需要推計条件

本節では TREES による 2050 年の推計条件を説明する．参考として 2013 年，2030 年の条件についても併せて示す．

（１）人口・世帯数の想定

2013 年では，2015 年の国勢調査 [16] に基づいて世帯数を設定した．2030 年は，国立社会・人口問題研究所による日本の世帯数の将来推計 [17] における 2030 年の中位推計を使用した．2050 年については上記の推計結果が入手できないことから，2050 年では，上記の推計における 2035 年までの推計結果を外挿して 2050 年の各都道府県の世帯数を推計した．図 2 に家族類型別の世帯数の推計結果を示す．世帯数は 2013 年比およそ 5%減少しているものの，単身世帯が増加している．なお，将来推計においては，世帯属性情報（世帯年収，住宅の所有関係，建築年）は平均的な属性を与え，これら以外の属性情報によってエネルギー消費決定要因の世帯間の違いを反映している．

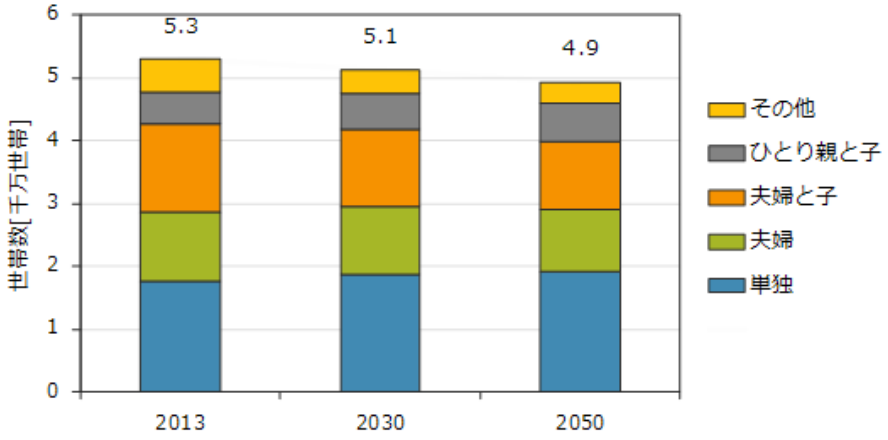


図 2　2013 年，2030 年，2050 年の世帯構成

（２）住宅の断熱性能

本研究室開発の住宅熱性能ストックモデル[13]を用いて住宅の断熱性能の推移を推計した．本モデルでは，まず，新築住宅における住宅の熱性能基準適合率の過去の変化を回帰して，将来にわたる変化を外挿して算出する．次に，住宅の新築，減失を考慮して住宅ストックの熱性能の比率を推計する．

地球温暖化対策計画[19]では，新築住宅に対して 2020 年までに段階的に断熱性能基準への適合を義務化する措置を講ずるとされている．2050 年では，全ての住宅ストックが平成 11 年基準に適合すると想定した．図 3 に 2050 年までの住宅ストックの熱性能構成比の推計結果を示す．なお，2030 年の数値は，2020 年に新築住宅における平成 11 年基準の適合率が 100%になるように 2019 年まで基準適合率が線形で上昇すると想定して，住宅熱性能ストックモデル[13]を用いて 2030 年の住宅ストックにおける基準適合率を推計したものである．

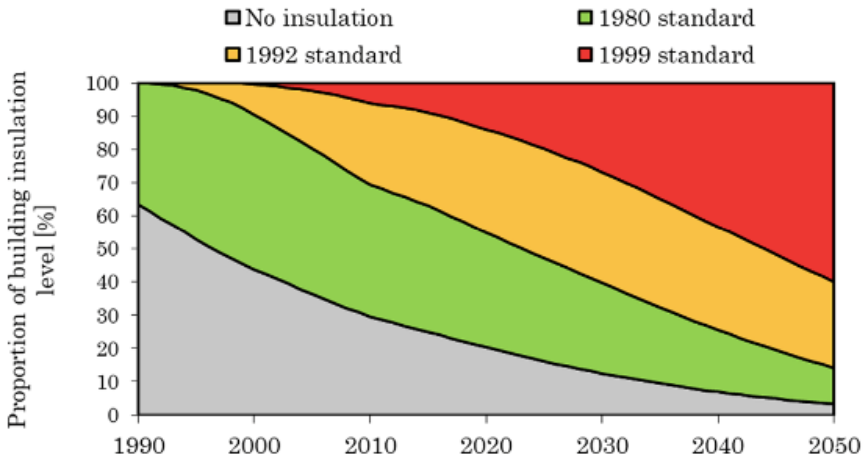


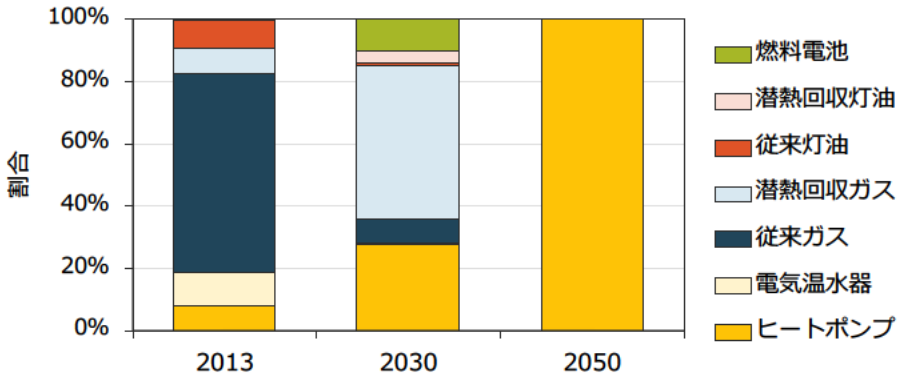
図 3　住宅ストックの熱性能構成比の推計結果

（３）暖冷房・給湯機器のエネルギー効率及び普及率

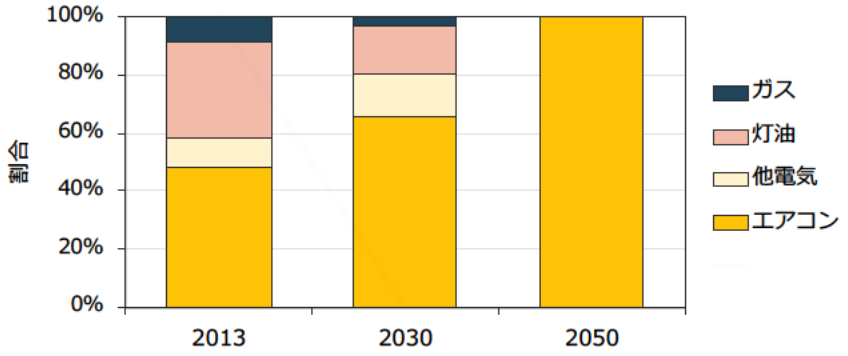
図 4 に暖冷房・給湯機器の普及率を示す．地球温暖化対策計画[19]における 2030 年の高効率給湯器の目標台数は，ヒートポンプ給湯機 1400 万台，潜熱回収型給湯器 2700 万台，燃料電池 530 万台である．それらの高効率給湯器が導入された結果，従来型給湯器は 2030 年の段階でほぼ淘汰されることが予想される．2050 年においては，エネルギー需要が全電化し，2050 年までに全給湯器ストックがヒートポンプ給湯機に置き換わることを想定した．また，2050 年では，現状普及しているヒートポンプ給湯機と同程度の効率（定格 COP が 4.2）の機種が普及するとした．なお，2030 年の数値は，地球温暖化対策計画に記載されている高効率給湯機の導入が実現されたことを想定して推計したものである．

世帯の暖房機器の種類は，住宅設備決定モデル[4]によって決定している．本モデルでは，暖房・給湯用途に対して同じ熱源の機器を選択する傾向があることを考慮して，暖房機器は給湯器の種類と世帯属性情報から確率的に決定している．2050 年では全電化されることを想定し，全ての世

帯が暖冷房にエアコンを使用することを想定する．また，住宅熱性能の向上に伴ってこたつや電気カーペットなどの補助暖房器具の使用も停止するものとする．



(a) 給湯器



(b) 暖房機器

図 4　各ケースにおける暖房・給湯機器の普及率

（4）照明・家電機器のエネルギー性能の向上

照明については，2013 年では標準的な照明を想定し，2050 年では全ての世帯で LED が採用されると仮定した．家電機器のエネルギー効率および保有数量の想定を表 1 に示す．本想定には長期エネルギー需給見通し関連資料[20]等を参考としている．設定の概要を以下に示す．

- テレビ，冷蔵庫の保有台数は保有状況予測モデル[5]から決定した．近年の省エネ性能カタログによると，近年のテレビ・冷蔵庫の高効率化はほぼ収束していることから，2050 年において全てのテレビ･冷蔵庫の効率が 2017 年製の最高性能機種相当の効率と一致することを想定した．
- そのほかの家電機器の保有数量は家電機器ストックモデル[13]により決定した．将来推計においては，過去の保有数量の変化を回帰し，その傾向が将来においても持続するとして各年の平均保有数量を推計している．エネルギー効率の変化はないと想定した．
- エアコンのエネルギー効率はエアコン保有統計モデル[22]を用いて想定した．2050 年では一律定格 COP を 6 程度となるよう設定した．

表 1　推計で想定された機器性能

Appliances considered in this study.

Appliance or system	Energy consumption				Number of appliances (Unit/household)	
	Unit	2013	2050	stand-by power***	2013	2050
Television	W/household*	308	71	0.2 ~ 0.7 W/unit	2.26	1.98****
Refrigerator	kWh/year/ household*	686	324		1.22	1.15****
RAC – 2.2 kW	APF (kW/kW) **	4.07	5.93	–	–	–
2.5 kW	APF (kW/kW)	4.37	5.92			
2.8 kW	APF (kW/kW)	4.34	5.93			
3.6 kW	APF (kW/kW)	3.90	5.55			
Lighting (living room)	W/m^2	7.0	3.0	–	–	–
VCR (operation mode)	W/unit	35.7	26.4	1.48	1.44	1.18****
Personal computer (operation mode)	W/unit	36.1	20.4	1.01	1.28	1.39****
Dishwasher and dryer	W/unit	387.8	Same as 2013	1.38	0.31	0.34
Exhaust fan	W/unit	20.0	Same as 2013	-	1.0	1.0
24-h ventilation system	W/household	5.8 (apt.)	Same as 2013	-	-	-
Washing machine/dryer	W/unit	111.8/1251.7	Same as 2013	0.29	0.32	0.51
Hair dryer	W/unit	633.3	Same as 2013	-	0.86	0.86
Small lamp	W/unit	30.0	Same as 2013	-	1.0	1.0
Vacuum cleaner	W/unit	623.2	Same as 2013	0	1.4	1.4****
Clothes iron	W/unit	1212.5	Same as 2013	0	0.9	0.9
Shower toilet (stand-by, winter/summer/interim)	W/unit	-	-	24.3/3.36/13.5	1.0	1.4****
Electric foot warmer	W/unit	518.3	None	0.03	0.22	0
Electric carpet	W/unit	265.8	None	0.10	0.37	0
Audio system	W/unit	36.4	Same as 2013	2.86	0.85	0.84
PC peripherals (stand-by)	W/unit	-	-	3.87	0.66	0.66
Satellite TV tuner(stand-by)	W/unit	-	-	3.56	0.2	0.2
Telephone	W/unit	-	-	3.03	0.59	0.46
Rice-cooker (cooking/warming)	W/unit	240.6/18.6	Same as 2013	1.03	0.96	1.0
Gas/induction heating (IH) stove	W/unit	Function of no. of family members	IH only	0.39(IH)	0.23 (IH)	1.0
Microwave	W/unit	572.9	Same as 2013	1.24	1.04	1.07****
Toaster	W/unit	1,071.0	Same as 2013	0.04	0.77	0.77
Electric kettle (boiling/warming)	W/unit	815.8/32.9	Same as 2013	-	0.66	0.66

*These values are calculated from appliance efficiency estimated by the appliance efficiency transition model and the number of appliances owned estimated by logit models for appliances per household.
**APF (Annual Performance Factor) is the ratio of (annual heating and cooling load) to (annual power consumption) under standard conditions as defined by Japan Industrial Standard C9612:2013.[29]
***Stand-by power in 2050 is assumed to be the same as in 2013.
**** These values are limited to 1.0 by measure (B-2) in subsection 3.2.2.

２．３　比較結果

本節では TREES による 2013 年，2050 年のエネルギー需要推計結果を示し，LED シナリオの値と比較した．LED シナリオでは住宅におけるエネルギー需要を Thermal comfort と Consumer goods に分けて推計している．そのため，家庭部門のエネルギー需要の総量に加えて，熱エネルギー需要を満たすためのエネルギー需要とその他家電による電力需要に分けて結果を記述する．それぞれで扱う項目を表 2 に示す．

表 2　各エネルギー需要の集計において考慮した項目

分類	項目
熱エネルギー需要	**空調**，**調理**（ガスコンロ，IH ヒーター），**給湯**
家電による電力需要	**照明**，**冷蔵庫**，**洗濯機**，**テレビ**，**PC**，**調理家電**（炊飯器，電子レンジ，電気トースター），**その他**（衣類乾燥機，食洗器，電気ジャーポット，換気扇など）

２．３．１　熱エネルギー需要

LED シナリオでは，一人当たりの床面積と床面積当たりのエネルギー需要をそれぞれ想定して

掛け合わせることで，熱エネルギー需要の定量化を行っている．このことから，一人当たりの床面積と床面積当たりのエネルギー需要を比較する．

（1）床面積

図 5 に TREES での推計と LED シナリオそれぞれで想定された床面積を示す．日本では人口減少と一戸当たりの世帯員の減少が見込まれており，TREES による推計では 2013 年から 2050 年で一人当たりの延床面積が 32 m^2/capita から 40 m^2/capita に増加することが想定されている．LED シナリオが示す 30 m^2/capita と比較すると，2050 年度では約 1.3 倍の大きな値となっている．

TREES での推計において床面積を減少させて LED シナリオの値に近づけるには，床面積の比較的小さい集合住宅の割合を増加させる，一戸当たりの世帯人員数を増加させるなどすることが必要である．なお，全体の世帯数に対する集合住宅の割合を 75%にすると LED シナリオに近い約 32 m^2/capita にまで減少させることができる．しかし，日本では建築ストックの延床面積がエネルギー需要に及ぼす影響が小さく，延床面積を LED シナリオの値に近づけることは大きな効果をもたらさない．このようにエネルギー需要の延床面積に対する感度が小さいのは，LED シナリオにおいて Global North に属する国々（特に欧米）では 24 時間運転の全館空調が主流であるのに対し，日本では間欠かつ局所冷暖房が主流であることに起因する．

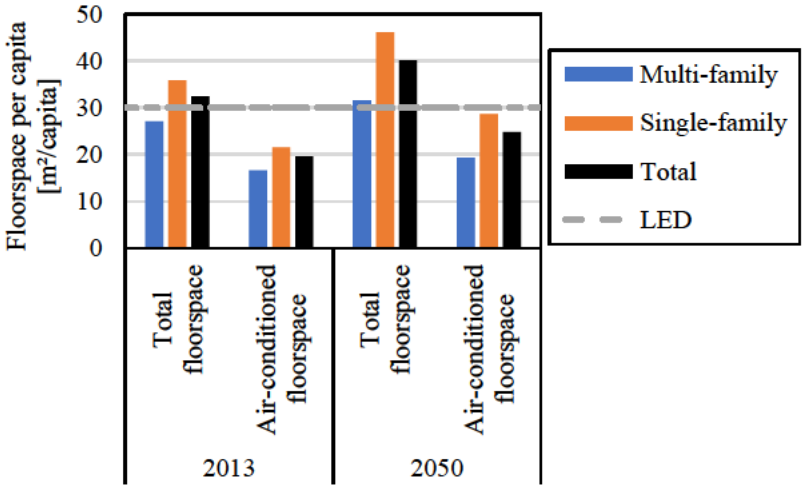


図 5　一人当たり床面積

なお，日本における空調面積に注目すると，TREES の推計では一人当たりの空調面積は 2019 年に 20 m^2/capita であり，2050 年には 25 m^2/capita になると想定されている．2050 年の空調面積は，LED シナリオの示す 30 m^2/capita よりも約 5 m^2/capita 小さい．

（2）延床面積あたりエネルギー需要

LED シナリオでは，熱エネルギー需要を，機器により生成される熱エネルギーである useful energy（UE）と機器により消費されるエネルギーの final energy（FE）に分けて示している．UE と FE それぞれについて，TREES による推計と LED シナリオと比較する．

図 6 に UE 需要の推計結果を示す．TREES による推計では，主に住宅の断熱性の向上により，2013 年から 2050 年で UE 需要がおよそ 30%削減されると予想された．一方，LED シナリオでは，年 3%の建築の改修を 30 年間想定することで，およそ 75%の大きな削減が予想されている．2050 年の推計値では，TREES の値が LED シナリオの値よりも 50 MJ/m² 以上大きくなっている．これには，日本の住宅の断熱性能（およびその基準）が諸外国と比較して低いことが強く影響していると考えられる．大幅に UE 需要を削減して LED シナリオの基準に近づけるための対策としては，日本の建築物の外皮基準を見直すこと，機器集約により効率的な熱エネルギー利用を行うことなどが挙げられる．

なお，本研究の推計結果では給湯用途を熱需要に含めたが，LED シナリオではここに含まれているか不明である．この点について今後確認する必要がある．含まれていない場合，2050 年の暖冷房熱需要は LED の 2050 年の需要よりも小さく，同程度の需要が想定されていると考えられる．

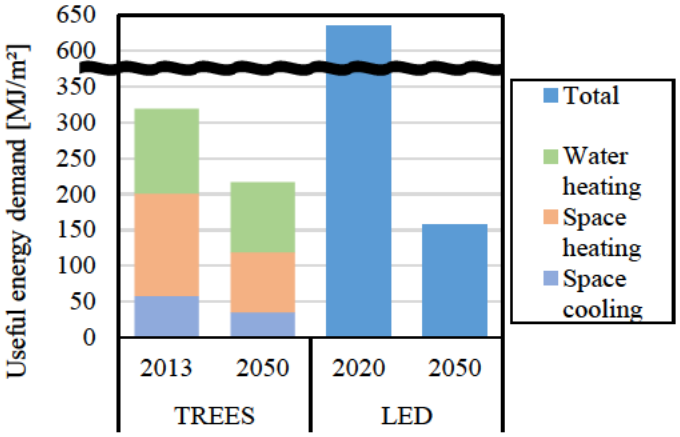


図 6　延床面積当たり useful energy demand（機器生成熱量）

図 7 に FE 需要の推計結果を示す．2050 年の FE 需要については，UE 需要と異なり，TREES の推計値が LED シナリオの値を大きく下回っている．これは，推計においてエネルギー効率の仮定が大きく異なることによる．LED シナリオでは，2050 年の FE/UE 効率（小さいほど良い）に 1.1（COP では 0.91 相当）としており，比較的保守的な仮定であると考えられる．一方，TREES による推計では，化石燃料を消費する機器の全電化（空調にはエアコンが，給湯にはヒートポンプ給湯機が，調理には IH ヒーターが使用される）の仮定により，FE/UE 効率が 0.25（COP では 4 相当）と非常に小さくなっている．空調機と給湯機はどちらも一般的に寿命が 20 年以下であること，日本の住宅では既にエアコンが主流であり機器交換がしばしば困難でないことを踏まえると，その仮定は十分現実的なものだと考えられる．

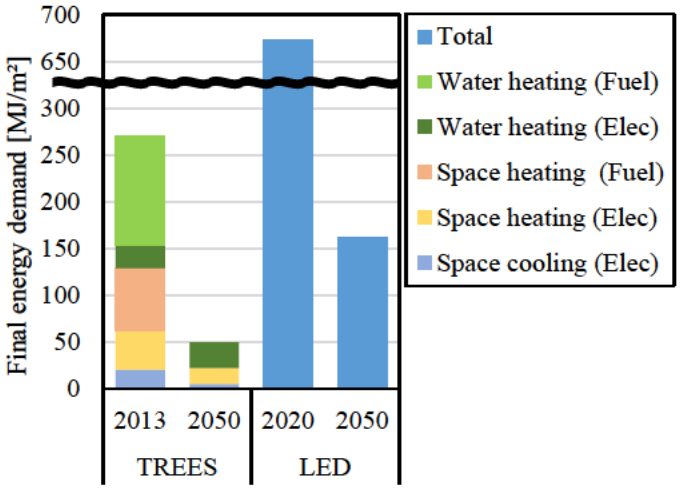


図 7　延床面積当たり final energy demand（機器消費エネルギー量）

２．３．２ 家電機器の電力需要

図 8 に推計結果を示す．TREES による推計と LED シナリオで住宅の有する機器の想定が様々異なると考えられるが，全体としては，TREES による 2050 年の家電電力消費の推計値が LED シナリオの想定と概ね同じ水準だと言える．なお，TREES モデルの Water heater は図 7 に示した Water heating と同じ数値である．特に差異が目立つ項目としては，「その他」が挙げられる．大きな差異の原因にはエネルギー効率の想定の違いのみでなく，推計において考慮する機器種や機器の分類条件の差異なども考えられる．この点について，TREES と LED シナリオの設定条件をそれぞれ詳細に確認する必要がある．

なお，調理について，本推計では炊飯器，電子レンジ，電気トースターの電力消費を考慮している．食文化の差異により他の Global North の国々と利用する機器が異なるであろうことに注意が必要である．

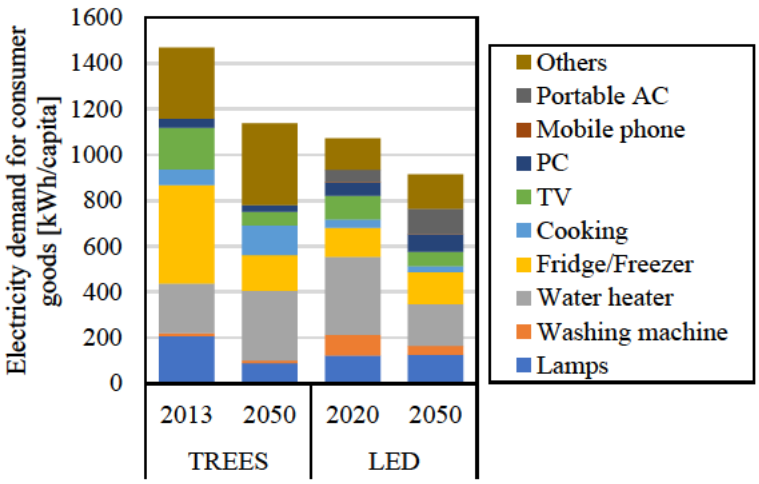


図 8　一人当たり家電電力消費量

２．３．３ 家庭部門最終エネルギー需要

図 9 左に TREES モデルにより推計した日本の家庭部門最終エネルギー需要を示す．建築物の断熱性能向上や機器の全電化，エネルギー効率向上等により，2013 年から 2050 年にかけて一人当たりの最終エネルギー需要が約 58%削減されることが予想されている．一方で LED シナリオにおける北半球（Global North）の家庭部門最終エネルギー需要推計（図 9 右）では，2020 年から 2050 年にかけて約 65%の削減が示されている．2050 年の値としては，TREES の推計値が LED シナリオの値よりも小さくなっている．しかし，エネルギー需要の削減幅で見ると，LED シナリオの推計値が TREES よりも大きな値を示している．

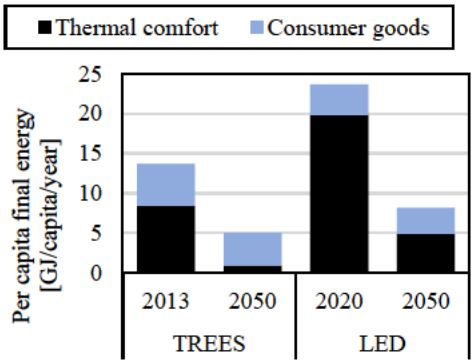


図 9　TREES モデルと LED シナリオによる一人当たりの家庭部門最終エネルギー需要推計結果

２．４　考察

TREES による 2050 年の日本の家庭部門エネルギー需要推計結果を LED シナリオの Global North と比較した．結果からは，2050 年の日本の家庭部門のエネルギー需要について，TREES の推計結果が LED シナリオよりも小さいことが示された．特に，熱エネルギー需要に関しては，ヒートポンプ技術の普及により大幅なエネルギー需要の削減が可能であり，機器普及状況を考慮すると実現性も高い．

LED シナリオで考慮されているが TREES で考慮されていない対策のうち，特に重要なものとして情報化の進展による変化が挙げられる．具体的には，機器の集約とシェアリングの増加である．図 9 では 2050 年の TREES の推計結果が LED シナリオの値を下回っているが，家電機器のエネルギー需要に注目すると，TREES の推計値が LED シナリオの推計値を上回っている．このことは家電機器についてより大幅なエネルギー需要削減が望まれることを示唆しているが，そこに次に説明する機器の集約と情報化の進展により可能となる諸対策が適用できると考えられる．

現在，多くの家電製品が使用されているが，その多くが単一の用途（サービス生成）に利用されている．一方で，スマートフォンやパーソナルコンピュータなどの情報機器は多くの用途に使用可能である．これらの多くの機能を有する機器により単一用途の機器を代替する，つまり，多

機能機器への集約を行うことにより，範囲の経済により全体のエネルギー需要を小さくすることができる．また，今後の技術革新によってさらなる集約が可能になることが予想される TREES モデルによる推計ではこのような機器の集約の効果を考慮していない．LED シナリオでは機器の集約効果について，カメラやラジオ，携帯電話など 15 の機器をスマートフォンへ集約することにより消費電力が約 99%，待機電力が約 97%削減されると推計しており，同様に日本においてもある程度の削減ポテンシャルが存在すると考えられる．

シェアリングについても TREES モデルは考慮していない．情報化はリアルタイムで空間や機器の需要と供給をマッチングすることを可能とするため，情報化の進展はシェアリングを進展し，余剰資源の有効活用により，エネルギーサービスの提供効率を向上させると考えられる．LED シナリオでは，エネルギー消費機器の台数やモビリティ需要の増加を抑制するものとして位置付けられている．加えて，LED シナリオには明記されていないが，情報化は人々の生活様式を変化させると考えられ，柔軟な勤務形態の選択や新たなコミュニケーションツールの活用が可能となることは，移動や滞在，機器使用の様子を変化させ，将来のエネルギー需要に大きな影響をもつと考えられる．

３．IPCC 第 6 次報告書の Buildings，Sufficiency の整理

気候変動に関する政府間パネル(IPCC)は 2021 年から 2022 年にかけて第 6 次評価報告書(AR6)を発表し，第 3 作業部会は 2022 年 4 月に報告書「気候変動 － 気候変動の緩和」[24]を発表している．本報告では，建築物に関する気候変動緩和を扱った第 9 章 Buildings[25]とエネルギー需要に関する知見をまとめた第 6 章 Demand, services and social aspects of mitigation[26]から緩和策について特に重要と考えられる内容をまとめた．以下では３．１節に Buildings，３．２節に Demand, services and social aspects of mitigation について説明する．３．３節では日本における民生部門の対策の概要を示すとともに，IPCC 報告書でまとめられた知見からの示唆を考察する．

３．１ Buildings

（１）排出量の実態

建築物は 2019 年において CO_2 換算 12Gt 相当の温室効果ガス（GHG）を排出し，全世界の GHG の 21％を占める．このうち 57％は電力（関節排出）に由来し，24％は燃料等の使用による直接排出，残りの 18％は建設等使用段階以外のライフステージに起因する．このうち 95％は CO_2 によるものである．最終エネルギー需要は 128.8 EJ と報告されており，そのうち 43 EJ は電力，最終エネルギー需要の 7 割は家庭部門によるものである．1990 年から 2019 年の 20 年間で CO_2 排出量は 50％，最終エネルギー需要，電力需要はそれぞれ 38％，161％増加した．

（２）Sufficiency-Efficiency-Renewable framework

報告書では CO_2 排出量の経年変化を示すとともに，茅恒等式の考え方に基づいて(1)式により変化がもたらされた要因を分析している．

$$CO2 = Pop \times \frac{m^2}{Pop} \times \frac{EI}{m^2} \times \frac{MT_{CO2}}{EI} = Pop \times Suff \times Eff \times Ren \quad (1)$$

ここで *CO2* は世界全体，あるいは，国地域の CO_2 排出量[$MtCO_2$/年]，*Pop* は人口[人]，m^2 は建築物延床面積[㎡/人]，*EI* は建築物床面積当たり最終エネルギー需要原単位[GJ/(㎡・年)]，MT_{CO2} は最終エネルギー需要当たりの CO_2 排出量[$MtCO_2$/GJ]である．人口 *Pop* を除くと CO_2 排出量は 3 つの比（因子）の積で与えられており，それぞれの因子は Sufficiency（*Suff*），Efficiency（*Eff*），Renewable(*Ren*)の高低を表す指数として解釈される.分析枠組みは頭文字をとって SER framework と呼ばれている.

Efficiency は床面積当たりの最終エネルギー需要を表しており，建築物の断熱性能の向上や空調システムのエネルギー効率改善などの対策が代表的な緩和策である．Renewable は 1 単位の最終エネルギー需要の利用に伴って排出される CO_2 を表す．必ずしも再生可能エネルギーの導入量を指すものではなく，電力システムの CO_2 排出係数の向上によっても向上するが，建築物において適用される緩和策という観点から再生可能エネルギーを表す「Renewable」が指数の名称として使用されている.Sufficiency は一人当たりのサービスの需要を表す指数であり，一人当たりの建築物床面積の削減など，サービス需要の削減に資する緩和策のすべてが含まれる.Sufficiency については第 3 章にまとめるが，その考えを適用した場合，次のような緩和策が検討可能となる：

(1) 建築物やエネルギー消費機器の使用によってもたらされるサービスの要求水準を下げること
(2) モノの所有ではなく，使用・サービスの享受を志向すること
(3) 使用する床面積，機器のサイズを小さくすること
(4) 空間や機器を他者と共有すること

（３）緩和策に関する知見

SER framework を用いた分析は過去の実績値のみではなく，地球温暖化による温度上昇を 1.5℃に抑える道筋を実現しうるシナリオ(炭素回収貯留など不確実性が高い将来技術に頼らずに 1.5℃を達成する Low Energy Demand シナリオ[1)]を含む）にも適用され，将来における削減ポテンシャルについても言及されている．主な結果を以下に示す.

- 1990 年から 2019 年の 20 年間における CO_2 排出量は 50%増加した．これは *Pop* 28%，*Suff* 52%，*Ren* 16%の増加，*Eff*ー49%の変化による．エネルギー効率向上による削減効果は *Suff*（一人あたりのサービス需要）の増加に相殺されている.
- 開発途上国では人口増加が変化の主要因となっている.
- 一人当たりの床面積は増加傾向にある．これは特に住宅床面積の増加によるものである.
- 新築建築物の低いエネルギー性能（特に開発途上国），省エネルギー改修の頻度の低さ（特に先進国）がエネルギー性能向上の障壁となっている.
- 収入の増加に伴ってエネルギー消費機器の使用頻度，所有台数，機器容量が増加しており，エネルギー消費を増加させている.
- 建築物で使用されるエネルギーの大部分は化石燃料由来のエネルギー供給に依存している.
- 2050 年までのベースライン排出量は 13.5$GtCO_2$ と推計されている.
- 2050 年までのポテンシャルの 17%は Sufficiency に関連するものである.

このほか，国地域単位で行われた研究についても取りまとめられている．2050 年までのベースライン（対策が行われない場合の予測値）と比較して，欧州，北米に関する研究では最高で 85%，アジア太平洋地域では 45%の削減が実現可能であると示されている．これらの研究を全世界でまとめると，2050 年には 8.2Gt の削減ポテンシャルが存在し，ベースライン排出量の 61%に相当する．この削減の 66%は途上国における削減によるものである．削減費用は Sufficiency に関するもの，照明や各種エネルギー機器の高効率なものへの置き換えは削減費用が 0 USD/tCO_2 未満（費用を上回る経済メリットがある）ものが多い．現時点で高い性能を持つ建築物を新築の標準モデルとする場合，先進国では削減費用は 20 USD/tCO_2 未満，途上国では 100 USD/tCO_2 未満と推計されている．既築の場合，改修による性能向上が大きなコスト増にならないことを示す事例が多数示されているが，多くの事例で削減費用が 0～200 USD/tCO_2，さらには 200 USD/tCO_2 以上になる可能性も示されている．削減ポテンシャルを顕在化するためには 2020 年から 2030 年の 10 年間が重要であり，産業転換によりノウハウ，技術を浸透させることが不可欠と述べられている．世界各国でゼロエネルギー条件（建築物で消費するエネルギーと生産するエネルギーが釣り合う）を満たす，あるいは，それに近い建築物の実現可能性が確認されている．

（4）課題として挙げられていること

報告書では最後に課題（Research gap）が述べられている．主要なものは次のとおりである．

- 開発途上国における削減ポテンシャル，費用に関する知見，削減検討を行った事例が不足している．
- 地域固有の知見は十分にまとめられていない．また，それらを取り込んだ緩和策の設計に関する検討は不足している．
- 排出量やエネルギー需要に関する業務施設に関する検討が不足している．
- Sufficiency に関する削減策に関する知見が不足している．
- 建築物のエネルギー消費に関する循環型経済・シェアリング経済に関する知見が不足している（特に，体系的整理，削減ポテンシャル，対策の実施実態，採用意思に関するもの）
- 気候変動影響に関する文献の多くが熱的快適性を扱うものであり，建築物の構造，材料，建設，エネルギーに関する気候変動影響，エネルギー消費，排出量に及ぼす影響関する知見，パッシブ技術の適応面での評価が必要である．また，検討が不足している地域が存在する．

３．２ Sufficiency

AR6[26)]では IPCC 報告書において初めて Demand, services and social aspects of mitigation に関する章が追加された．エネルギーサービスに限らず，人はエネルギー・資源を消費したいのではなく，尊厳ある生存，人間らしい生活（栄養，移動，コミュニケーション，快適さ，物質的な幸福などを含む）を実現し，そのほかの需要を充足するためにサービスを必要とし，サービスの提供過程でエネルギー・資源が消費される．また，サービス需要や提供方法は社会的に形成されるものであり，文化的，地域的に多様性がある．このような需要に焦点を当てることにより，供給側の対策以外の緩和策を選択肢に含めることができる．

需要に関する対策は，短期的に有効な緩和策として，また，長期的な技術選択，行動，ライフスタイルの変化として実現されるものであり，生産・サービス提供システム，関連するインフラ，社会技術的変化との相互関係を持つ．需要側における緩和策の導入は，供給側での対策を柔軟にし，不確実性の高い技術への依存度を下げることを可能とする[28]．あらゆる部門における需要の削減は対応する各セクターのGHG排出削減に大きく貢献すると試算されており，建築物では2050年におけるベースラインに対して5.7 $GtCO_2$，食料生産では8 $GtCO_2$，交通・陸上輸送では6.5 $GtCO_2$，産業部門では5.2 $GtCO_2$の削減ポテンシャルが存在すると推計されている．

（1）Decent Living Standards

持続可能な消費と生産は，「Doing more and better with the same」を志向することであり，生活の質を高めながらライフサイクル全体を通じて資源の使用，劣化，汚染を減らしつつ，幸福度を高める考え方である．エネルギーは基本的ニーズを満たし，開発を進めるために必要なものであるが，歴史的に観測されてきたように基本的ニーズの充足や開発の推進に伴って排出量を増加させる必要はない．また，「適切なサービス需要」を考えるにあたり，生活の質（Quality of life：QoL）の向上，幸福度（Happiness）の改善，持続可能な開発を損なうことは考えられておらず，「すべての人」にとって適切な水準の幸福（Well-being）を実現する需要を実現することの重要性が説明されている．

Decent Living Standards（DLS）は日本語で「人間らしい生活水準」と訳されており[27]，サービスの消費が一定の水準を超えると人の幸福の向上に貢献しないという充足性を考慮した生活の水準である．すべての人に対してDLSを最も排出量の小さい方法で充足する道筋を考えることで大幅にGHG排出量を削減することができると考えられる．また，DLSを充足する方法は文化，地域，技術，社会的選好等によって異なることが知られており，このことは様々な方法によりDLSを充足しうることを意味する．

現時点では住居，栄養，モビリティ，コミュニケーションの分野においてDLSが充足されていない地域が存在しており，一方で先進国等ではDLSを超える水準での消費が行われている．DLSに相当する最終エネルギー需要は一人当たり13～18.4 GJ/(人・年)である．実態は5~200 GJ/(人・年）と報告されており，現時点では不公平な消費実態がある．

（2）Avoid-Shift-Improve framework

報告書では需要に関する緩和策を，Avoid，Shift，Improve（まとめてASI）により整理している．ASIはもともと交通部門で開発されたものであり，Avoidは不要なサービスを避ける対策である（移動の取りやめなど）．Shiftは代替性を持つ手段への変更（自動車交通に対して公共交通の利用など），Improveは一つの手段における改善（自動車という選択肢の中での電気自動車の利用など）を意味する．ASIの枠組みに基づいて導出される具体的な対策群を表3に示す．もの，栄養の項目を除くと都市・建築物に関連して多様な対策が考慮可能である．これらを包括的に取り込んだ検討にGrublerら[1]によるLow Energy Demand（LED）シナリオがある．この分析では現時点で不確実性の高い供給側の技術に頼ることなく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．ASIを推進する政策としては様々なものが考えられるが，現時

点では Avoid，Shift に関するものは少なく，Improve に当たる緩和策が政策の主な対象となっている．

表 3　ASI に基づいて整理された緩和策の例（報告書 [24]Table 5.1 に基づいて作成）

Service	Avoid	Shift	Improve
交通	移動距離の削減策 よりよい交通計画，土地利用計画の実践，スマートロジスティクス，テレワーク，コンパクトシティの形成，長距離飛行の削減，休日の設定	移動手段の変更による移動距離当たりのエネルギー消費量の削減	移動体の技術開発による効率改善 移動体の軽量化，水素自動車・電気自動車への代替，エコドライブの実践
住宅・建築物のシェルター機能	居住面積の削減策 人間らしい水準の住宅への居住，居住空間における他者との共用部の共有，多世代住宅の利用	床面積当たりの資源投入量の削減策 建築物の省資源型設計，戸建住宅ではなく集合住宅の選択	床面積当たり CO_2 排出量が小さい住宅の設計 木材資源の利用，低炭素集約型資源の利用
熱的快適性	健康的な室内設定温度の選択 快適な水準を超える設定温度の緩和，環境に応じた着衣量の変更，労働時間の変更	建築物内外温度差当たりのエネルギー消費を減少させる対策 庇，自然換気などによるパッシブデザインの利用など	新規技術の採用による建築物内外温度差当たりのエネルギー消費，エネルギー消費あたりの CO_2 排出量の削減 太陽熱利用，外皮熱性能向上，ヒートポンプの利用，地域暖房の利用
もの（製品利用）	1 つの製品から製造されるサービスの増加 長寿命化，シェアリング経済の構築	プロダクトデザインによる製品生産量当たり資源投入量の減少 資源効率性の高い設計	資源の代替による資源消費あたりの CO_2 排出量の削減 低炭素集約的資源・材料の利用，製造工程の改良，機器・設備利用の効率化
栄養	消費カロリー当たりの生産カロリーの削減策，消費するカロリーの最適化 日々の必要量，健康に適した水準への消費量の削減，生産過程，消費過程における廃棄食品の削減	食習慣の変更 反芻を行う動物の肉と乳製品から他のタンパク質源への代替	カロリー当たりの CO_2 排出の削減 農業生産の効率化，効率の良い食料品加工
照明	人工照明に対する需要の削減 人感センサーや照明制御の利用	人口照度を向上させる対策 建築設計の改良（昼光利用の促進に資するものなど）	高効率照明の利用 LED 照明の利用

（3）変革につながるメガトレンド

シェアリング経済，循環型経済，デジタル化は需要，Sufficiency に関する緩和策を革新的に進めうるメガトレンドとして認識されている．シェアリング経済，循環型経済はいずれも利用者の利便性を高め，資源消費を削減することに貢献するものであり，デジタル化はそれらを促進する構造を持つ．

サービス提供の文脈では，消費者がデジタル商品の購入，サービス加入，使用する機会が数多く存在する．デジタル化は，消費活動のあらゆる領域で新しい可能性を広げており，デジタルデータに基づくプラットフォームは，余剰資源の特定，提供，共有，取引，交換を可能にするとともに，消費者の嗜好やニーズに関する情報をリアルタイムでやり取りし，サービス提供をパーソ

ナライズ，差別化，自動化，最適化することを可能としている．デジタル化によりもたらされる変化は既存のサービス形態から革新的に異なる機能を提供する事例が多く，代表的な変化には余剰資源の利用，所有から利用へのモデル転換，より広いネットワークの中でのサービス提供，サービス提供システムの制御性向上など，複数のイノベーションに共通する魅力的な機能を実現可能としている．シェアリング経済の領域ではP2P（peer to peer）で様々なものをシェアするプラットフォームが構築されており，さらなる進展が予想されている．循環経済の領域では不用品の交換，製品ライフサイクルにおける追加的なマニュファクチャリング，高度なプロセス管理，フォルト検知，ジャストインタイム製造などが利用されるようになり，さらに製造過程のトラッキング，3Dプリンターの活用，スマート材料，自動解体などが登場している．

（４）変化に関する知見

変化に関する文献では3つの重要な知見が得られている．一つ目はサイズに関するものである．社会的，経済的，技術的に規模が大きいものは変化の速度が遅く，小さい（Granular）ものほど早く変化する．システムの構造が既存のものと異なる場合，システム変化はより長い時間がかかる．二つ目は複雑性に関するものである．複雑なシステムほど変化に時間がかかる．事例としてはCO_2の回収・利用・流通システム，水素社会が挙げられる．三つ目は人のつながり，システム構造，意味付け（価値づけ）により変化を加速させうるということである．このような特性から，行動変容やSufficiencyに関する緩和策は不確実性の高い複雑な技術的緩和策よりも早く普及し，大きな排出量の削減をもたらす可能性がある．

（５）課題として挙げられていること

報告書では最後に課題（Research gap）が述べられている．主要なものは次のとおりである．

- 人間の幸福度を測る指標の開発
  GDPは発展の規模を表す指標として用いられているが，人の幸福度を表す指標としては説明力が乏しい．指標はサービスの需要・提供・消費を含むものであることが望ましい．
- デジタル化が気候変動にもたらす影響の評価
  デジタル化によるGHG排出量の増加，デジタル化によって引き起こされるシステム変化がもたらす排出量の削減，社会格差がもたらす負の影響など十分な検討が行われていない．
- サービスに関するシナリオモデリング
  エネルギーや製品の供給側に関しては詳細なモデルによる分析が行われている．一方で，サービスに対する需要の形成，サービス需要に対する提供システム，それらに関する人々の活動について詳細なモデリングが行われておらず，例えば，考慮されるライフスタイルのパターンは非常に少ない．利用可能性が高まっている様々なデータに基づいて，それらを記述するモデル，モデルを用いたシナリオ分析が必要である．
- 個人，社会，システムの変化に関する動的特性の理解
  需要に関する社会変化，システム変化を記述するための知見が不足している．これまでに特定技術など限られた領域での社会変化が検討されているが，多様な領域の変化を統合した理解は進んでおらず，政策設計に資する知見が不足している．

３．３　日本の取り組みと課題

３．３．１　日本の民生部門を対象とする緩和策の長期計画

日本は 2021 年 10 月に閣議決定された地球温暖化対策計画[19]において 2030 年温室効果ガス排出削減目標を 2013 年比 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．2013 年度，家庭部門，業務その他部門における CO_2 排出は 208 $MtCO_2$，238 $MtCO_2$ であるが，2030 年度までの削減目標をそれぞれ 66%，51%と定めている．同計画が記載している削減目標を達成するための具体的な技術的変化を表 4 に示す.いずれも 2030 年度における CO_2 排出削減量を 2013 年度比で表している．対策は①住宅・建築物のエネルギー消費性能向上（住宅・建築物の新築対策，既築の改修，高効率照明，給湯設備の普及），②エネルギー消費機器のエネルギー消費性能向上，③エネルギー管理による運用改善に分類することができる．技術項目別の削減見込みは前述の 2030 年削減目標を下回るものであるが，その差分は主に電力 CO_2 排出係数の削減により実現されると計画されている．排出係数の目標は 2013 年度 0.57 $kgCO_2/kWh$ に対して 0.25 $kgCO_2/kWh$ である．

表 4　地球温暖化対策計画における削減目標を達成するための対策別削減見込み（削減見込み量の小さい対策は割愛した）

対策技術	家庭部門	削減見込み量 $MtCO_2$/年	業務部門	削減見込み量 $MtCO_2$/年
住宅･建築物のエネルギー消費性能向上（新築）	新築住宅の省エネルギー化	6.2	新築建築物の省エネルギー化	10.1
同上（改修）	住宅ストックの改修	2.2	業務施設ストックの改修	3.6
高効率照明の普及	同左	6.5	同左	6.7
高効率給湯機の普及	HP 給湯機，潜熱回収型給湯器，燃料電池の普及	9.0	HP 給湯機,潜熱回収型給湯器の普及	1.4
トップランナー制度による機器のエネルギー消費性能向上	家庭用トップランナー機器の普及	4.8	業務施設で使用されるトップランナー機器の普及	9.2
エネルギー管理による運用改善	HEMS 等によるエネルギー管理	5.7	BEMS 等によるエネルギー管理	6.4

2021 年に公表された第 6 次エネルギー基本計画[29]は，2050 年までにカーボンニュートラルを達成するために必要となる変化を示している．エネルギー供給については電力供給の脱炭素化，都市ガス，LP ガス，灯油等の化石エネルギーから，非化石エネルギーにより製造される水素や合成メタンなどへのエネルギー転換を進める方向性が示されている．民生部門はエネルギーの需要家として，電化，エネルギー転換へ対応することが求められる．このような技術選択はエネルギー供給へのアクセス性や気候の差異に伴う需要特性など様々な要因が大きな影響を持つことが知られており，その結果として技術採用において地域による差異が生じている．同計画では，地域

や建物毎の特性の違いを踏まえた対策が必要とし，需要サイドにおいて最適なエネルギー転換進めるための選択肢を追求するとしている．

このほか，住宅・建築物についても，「省エネルギー改修や省エネルギー機器導入等を進めることで，2050 年に住宅・建築物のストック平均で ZEH・ZEB 基準の水準の省エネルギー性能が確保されていることを目指す.」としている [29)p. 30]．ゼロエネルギーハウス（ZEH），ゼロエネルギービル（ZEB）とは，現行の一次エネルギー消費量に基づくエネルギー消費性能基準（次節に後述）に対して住宅は 20%以上，建築物は 50%以上の省エネルギーを図った上で，再生可能エネルギー等の導入により，エネルギー消費量を更に削減した住宅・建築物を意味する．

既存の努力の方向性だけでなく，地域からエネルギーシステムの転換を進める取り組みも始まっている．国・地方脱炭素実現会議はそのロードマップ [30)] を示し，全国で 100 の脱炭素先行地域を創出し，確立した仕組みを全国に展開することを計画している．

３．３．２　緩和策の推進手段

上記の①～③の対策は，エネルギー使用の合理化等に関する法律（通称，省エネ法）[31)] と建築物のエネルギー消費性能の向上に関する法律（通称，建築物省エネ法）[32)] により推進されている．

（１）住宅・建築物のエネルギー消費性能向上

建築物省エネ法は省エネ法の第 5 章「住宅・建築物部門」が移行されたものであり，2015 年に公布された．省エネ法第 5 章で目的とされていた住宅・建築物のエネルギー消費性能の向上に加え，同法は脱炭素化も目的に含む．2021 年時点では，建築物省エネ法の主な実施内容は規制措置，誘導措置である．規制措置は延床面積 300 ㎡以上の延床面積を持つ建築物を対象とし，一次エネルギー消費量で定義されるエネルギー消費性能指標について基準（省エネ基準という）を設け，基準を上回るエネルギー消費性能を備えることを義務としている（省エネ基準への適合義務）．同基準は 2013 年における省エネ法改正で定められた標準仕様（基準設定仕様）と同等の水準として定義されており，建築物の熱性能だけではなく照明，空調・換気，給湯などの主要設備の性能をカバーする．300 ㎡以上の住宅については同様に省エネ基準を定め，その達成を評価し届け出すること，設計の際に設計士から建築主に対して適合可否を説明することを義務としている．説明義務は 300 ㎡未満の建築物・住宅についても適用されている．ただし，分譲戸建住宅を年間 150 戸以上，注文戸建住宅を年間 300 戸以上，賃貸アパートを年間 1000 戸以上供給する事業者については，省エネ基準より 10%～25%高い基準（住宅トップランナー基準という）を設定し，各年度に供給するすべての住宅の平均値について基準への適合，加えて，外皮基準と呼ばれる住宅外皮の断熱性能に関する基準への適合を求めている．

建築物省エネ法の誘導措置では，建築物では省エネ基準よりも 20%，住宅では 10%性能が高い基準である誘導基準を設け，誘導基準への適合によりインセンティブが得られる制度としている．その例は建築物容積率特例，低金利住宅ローンであり，誘導基準への適合が各種関連制度の評価基準として用いられている．2018 年度に届け出された事務所ビルのデータを分析した宮田ら [33)] の分析によると，62%の対象が省エネ基準よりも 15～35%良いエネルギー性能を有しており，取り組みは一定の成果をあげていると考えられる．

国土交通省と経済産業省，環境省は合同で脱炭素社会に向けた住宅・建築物の省エネ対策等の在り方検討委員会を設置し，2021 年 8 月に報告書を取りまとめている[34]．本報告書では，前述の第 6 次エネルギー基本計画に記載されている 2050 年の住宅・建築物の姿（ZEH・ZEB 基準の確保）を実現するために，2030 年までに，新築住宅・建築物が ZEH・ZEB 基準の省エネ性能を有し，新築戸建住宅の 6 割に太陽光発電が導入されることを目標としている．同研究会はこれを実現するためのロードマップを発表しており，1）省エネ適合義務化対象の拡大（300 ㎡未満の建築物への拡張，住宅外皮性能基準の適合義務化等），2）省エネ基準，誘導基準の引き上げ（ZEH，ZEB 基準を省エネ基準にし，誘導基準をさらに引き上げる），3） 誘導基準を上回る性能を実現する取り組みの促進を計画している．また，ロードマップが実現された場合，2050 年の住宅ストックは平均で現行省エネ基準よりも 10%，建築物は 22%エネルギー性能が高くなると試算している[35]．

（２）エネルギー消費機器のエネルギー消費性能向上

エネルギー消費機器のエネルギー消費性能は省エネ法のトップランナー制度により向上が図られている．トップランナー制度では，基準策定時にエネルギー消費効率の指標を定め，目標年度から 3～10 年程度前におけるトップランナーグループの効率指標とその時点での技術開発の将来見通しを考慮して基準値を定める．そのうえで，目標年度以降に対象製品の製造・輸入を行う事業者に対して，製品の平均値として基準以上の性能を持つことを求める．同制度は照明器具やテレビ，冷蔵庫など民生部門で使用される 28 の機械器具を対象としており，エネルギー性能の向上を目指して運用されている．この制度により，機器更新を通して経年的に機器ストックのエネルギー性能がなりゆきで向上する．

（３）運用改善

上記の施策により住宅・建築物，エネルギー消費機器ストックの経年的な性能向上が担保される．省エネ法では年間のエネルギー消費量が原油換算 1500kL/年以上の事業者を管理指定工場として定め，エネルギー管理総括者及びエネルギー管理企画推進者の選任，エネルギー使用状況の定期報告，中長期的（3～5 年）にみて年平均 1%以上のエネルギー消費原単位又は電気需要平準化評価原単位の低減に向けた努力，これを実現するための中長期的な計画の作成・届け出を義務としている[31]．省エネ法は，1%のエネルギー消費原単位の削減（努力義務）に加えて，ベンチマーク制度を運用している[36]．ベンチマーク制度は業種・分野別にエネルギー消費効率を定義し，中長期的に目指すべき水準（ベンチマーク目標という）を定め，その達成を求めるものである．2022 年時点で業務部門のうち貸事務所，国家公務，コンビニエンスストア，百貨店，食料品スーパー，ショッピングセンター，ホテル，大学，パチンコホールの 9 業種を対象としている．同制度は事業者の省エネ状況を業種・分野別の指標を用いて評価することに特徴があり，事業者は S，A，B，C のクラスに格付けされ，相対的にエネルギー性能の良し悪しが評価される．ベンチマークは国内事業者の分布において上位 10%から 20%となる事業者が満たす水準として設計され，S クラスはベンチマークを達成した事業者が格付けされる．2019 年度の定期報告に基づく評価[36]ではコンビニエンスストアの 47%，百貨店業の 27%，食料品スーパー業の 20%がベンチマーク指標の目標水準をクリアした．貸事務所業，ホテル業，ショッピングセンター業は 20%未満であっ

た．前述の第 6 次エネルギー基本計画では，ベンチマーク目標の見直しや対象業種の拡大に取り組むとしている．

３．３．３　脱炭素化に向けた課題

国は温室効果ガス排出量の削減目標を示すとともに削減を実現するための道筋を示している．新築住宅・建築物，トップランナー制度対象機器のエネルギー消費性能向上は法的に対策普及が担保されているが，今後予定されている性能基準の強化については経済的負担や技術基盤の欠如など社会・経済的障壁がある．また，既存住宅・建築物ストックのエネルギー消費性能を向上させる施策は現時点で有効なものが存在しない．住宅ストックでは約 5000 万戸のうち外皮性能にかかわる現行の省エネ基準を満たしているストックの比率は 2019 年時点で 13%であると試算されており [37]，その対策は重要である．同様に③エネルギー管理による運用改善についても対策を直接普及させる施策は現時点で存在しない．

IPCC 報告書にまとめられた知見を考慮すると次の課題が挙げられる．

- 住宅・建築物，エネルギー消費機器の対策は，寿命による更新においてエネルギー性能基準を満足するように求める対策を基本的手段としている．2050 年までの途中経路において早期にストック全体での削減を実現する経路を積極的に探索するべきである．カーボンバジェットを考慮する視点が必要であろう．
- 建築物に関する対策について費用情報が十分に整備されていない．また，地域固有の知見は十分にまとめられておらず，それらを取り込んだ緩和策の設計に関する検討は十分に行われていない．
- これまでに日本で計画されている緩和策は，Avoid， Shift， Improve のうち，Improve を志向する技術的対策が主たる対象になっている．緩和策の幅を広げることはより大きな削減をより早期に実現するために有効であると考えられる．
- Sufficiency に関する緩和策（Avoid， Shift に対応するもの）に関する知見が不足している．日本では Sufficiency に関する体系的検討が行われていない．具体的には，緩和策のメニューの明確化，削減ポテンシャルの推計，推計のためのモデル・分析方法開発，具体的な転換シナリオの開発，転換のための社会実験，プラットフォーム構築などが有効であると考えられる．日本版 Low Energy Demand（LED）シナリオの開発も有意義であろう．

４．分析枠組みの構築

Grubler ら [1]の Low energy demand（LED）シナリオは LED シナリオでは，Activity level と Energy intensity の積として将来の世界のエネルギー需要を定量化している．ここで，Activity level はエネルギー需要の主な発生要因，Energy intensity はエネルギー利用における効率を表し，例えば熱的快適性を提供するためのエネルギー需要に関しては，一人当たりの床面積が前者，床面積あたりのエネルギー需要が後者として考慮されている．エネルギー需要の推計は世界の国々を Global North（主に北半球に遍在する先進国群）と Global South（主に南半球に遍在する途上国群）の二つに分けて行われており，Activity level と Energy intensity それぞれについ

て，都市化や情報革命，生活の質向上など，世界的な社会変化を考慮した検討が行われており，全世界的に重要な知見を提供している．一方で，本研究では LED シナリオについて次の課題があると考えている．

- LED シナリオでは行動変容を含むエネルギー需要削減のための対策が考慮されているが，利用可能な対策のすべてが網羅されているわけではない．そのため，対策として実施可能な技術的・社会的変化を網羅してリストアップし，その効果を定量化することは重要であると考えられる．
- 種々の社会変化の影響が合わさった結果として Activity level と Energy intensity の変化として削減量を定量化している．このような推計方法から，対策間の相互作用が十分に考慮されていない．そのため，対策導入効果の推計値には大きな誤差が含まれる可能性がある．
- LED シナリオではエネルギー需要の定量化を二つの大きな地域に集約して行っている．そのため，対策の導入可能性，導入効果の両方で地域性が考慮されていない．LED シナリオ，あるいは，HwL シナリオの日本への適用を考慮する場合，日本の文脈を考慮したシナリオ構築，効果推計が必要である．

以上の背景から，今年度，対策を網羅するための枠組みを開発するとともに，対策の導入効果を定量化するための方法を検討した．本報告は未発表の内容を含むため，報告を割愛する．

５．まとめ

本報告書では 2022 年度に大阪大学が EDITS プロジェクトの一環として実施した研究の成果を報告した．主な成果は以下のとおりである．

- 東京大学杉山先生が主導している EDITS model complementarity exercise に参加し，大阪大学が開発している日本のエネルギー需要モデルの推計結果を提供した．2050 年の日本の家庭部門のエネルギー需要について，2050 年における日本の家庭部門のエネルギー需要は LED シナリオで想定されている水準よりも小さいことがわかった．一方で，LED シナリオで考慮されているが TREES で考慮されていない対策のうち，特に重要なものとして機器の集約とシェアリングがあり，今後，それを含めた検討を行う．
- 日本における対策の現状を整理したところ，住宅・建築物，エネルギー消費機器の対策は，寿命による更新においてエネルギー性能基準を満足するように求める対策を基本的手段としていることが分かった．2050 年までの途中経路において早期にストック全体での削減を実現する経路を積極的に探索するべきである．また，建築物に関する対策について費用情報，地域固有の知見は十分にまとめられておらず，それらを取り込んだ緩和策の設計に関する検討が必要である．これまでに日本で計画されている緩和策は，Avoid，Shift，Improve のうち，Improve を志向する技術的対策が主たる対象になっている．緩和策の幅を広げることはより大きな削減をより早期に実現するために有効であると考えられる．特に，Sufficiency に関する緩和策（Avoid，Shift に対応するもの）に関する知見が不足している．

- このような課題に対して,本研究は拡張 ASI framework を提案した.本枠組みは Avoid, Shift, Improve を包括的に考慮することが可能である.加えて,人行動シミュレーションに基づき,対策の導入効果を定量化する枠組みを提案した．来年度以降，提案枠組みに基づく開発を行う.

参考文献

1) 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.
2) 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
3) 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.
4) 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.
5) 的場晴香, 杉山みなみ, 松岡綾子, 下田吉之, 山口容平: 家庭 CO2 統計とエネルギー最終需要モデルを用いた世帯間エネルギー消費差異の成因に関する研究, エネルギー・資源学会論文誌 41(5) 209 – 218 2020 年 9 月， https://doi.org/10.24778/jjser.41.5_209
6) 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
7) 松岡綾子, 山口容平, 上林由果, 下田吉之 (2019). 世帯属性情報に基づく湯はり頻度予測モデルの構築, 空気調和・衛生工学会論文集, No. 264, pp. 35-44
8) 松岡綾子ほか: 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, 第 84 巻, 第 757 号, pp.323-333, 2019.3
9) Shimoda, Y., Taniguchi-Matsuoka, A., Inoue, T., Otsuki, M., & Yamaguchi, Y. (2017). Residential energy end-use model as evaluation tool for residential micro-generation. Applied Thermal Engineering, 114, 1433–1442. http://dx.doi.org/10.1016/j.applthermaleng.2016.09.066
10) Taniguchi, A., Inoue, T., Otsuki, M., Yamaguchi, Y., Shimoda, Y., Takami, A., & Hanaoka, K. (2016). Estimation of the contribution of the residential sector to summer peak demand reduction in Japan using an energy end-use simulation model. Energy and Buildings, 112, 80–92.

http://doi.org/10.1016/j.enbuild.2015.11.064
11) 谷口綾子，下田吉之，山口容平：改正省エネルギー基準による大阪府家庭部門エネルギー消費削減効果の評価，日本建築学会環境系論文集，Vol.80，No.708，2015-2，pp.159-168
12) Yoshiyuki Shimoda， Tomo Okamura， Yohei Yamaguchi， Yukio Yamaguchi， Ayako Taniguchi， Takao Morikawa : City-level energy and CO2 reduction effect by introducing new residential water heaters， Energy， Vol.35， Issue 12(2010-12)， pp.4880-4891
13) 下田吉之ほか: 家庭用エネルギーエンドユースモデルを用いた我が国民生家庭部門の温室効果ガス削減ポテンシャル予測. エネルギー・資源 30 (3), pp.1–9, 2009.
14) 谷口綾子ほか: 日本の住宅エネルギー最終需要のモデル化と住宅熱性能改善の影響評価: 世帯詳細区分型都市住宅エネルギーエンドユースモデルの開発と応用 (3). 日本建築学会環境系論文集, 第 73 巻, 第 632 号, pp.1217–1224, 2008.10
15) Shimoda, Y., et al.: Evaluation of city-scale impact of residential energy conservation measures using the detailed end-use simulation model. Energy, 32 (9), pp.1617–1633, 2007
16) 総務省統計局: 平成 27 年国勢調査
17) 国立社会保障・人口問題研究所: 将来推計人口・世帯数.
18) 国土交通省: 今後の住宅・建築物の省エネルギー対策のあり方について（第二次報告案）. 2018.12.3. http://www.mlit.go.jp/report/press/house04_hh_000843.html 2019.11.8 閲覧
19) 内閣官房：地球温暖化対策計画（2021 年 10 月）
20) 経済産業省 資源エネルギー庁: 長期エネルギー需給見通し関連資料.2015.7 http://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/mitoshi/011/pdf/011_07.pdf 2018.2.16 閲覧
21) 森國太朗ほか: 高効率給湯器大量導入に伴う暖房機器ストックの変化予測. 第 34 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, pp.286-291, 2019
22) 山﨑知哉ほか; 家庭用エアコンの部分負荷特性の変遷を考慮したストック分布に基づく空調電力需要の推計, 第 34 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(2019), pp.274-279
23) UNFCCC “Glasgow Climate Pact”, グラスゴー気候合意（環境省暫定訳）, http://www.env.go.jp/earth/COP26 カバー決定「グラスゴー気候合意」環境省暫定訳.pdf (2021)
24) IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926
25) Cabeza, L. F., Q. Bai, P. Bertoldi, J.M. Kihila, A.F.P. Lucena, É. Mata, S. Mirasgedis, A. Novikova, Y. Saheb, 2022: Buildings. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on

Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.011

26) Clarke, L., Y.-M. Wei, A. De La Vega Navarro, A. Garg, A.N. Hahmann, S. Khennas, I.M.L. Azevedo, A. Löschel, A.K. Singh, L. Steg, G. Strbac, K. Wada, 2022: Energy Systems. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.008
27) 国立研究開発法人科学技術振興機構（JST） “SDGs 達成に向けた科学技術イノベーションの実践”, https://www.jst.go.jp/sdgs/pdf/sti_for_sdgs_report_mar_2021.pdf, 最終アクセス日 (20221130)
28) IPCC, 2018: Summary for Policymakers. In: 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 [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-24. https://doi.org/10.1017/9781009157940.001.
29) 内閣官房: “Strategic Energy Plan”, https://www.enecho.meti.go.jp/category/others/basic_plan/ (2021)
30) 国・地方脱炭素実現会議: “地域脱炭素ロードマップ” (2021)
31) 経済産業省資源エネルギー庁: “Overview of the Act on Rationalizing Energy Use”, https://www.enecho.meti.go.jp/category/saving_and_new/saving/enterprise/overview/
32) 国土交通省: “Act on the Improvement of Energy Consumption Performance of Buildings”, https://www.mlit.go.jp/jutakukentiku/jutakukentiku_house_tk4_000103.html
33) 宮田征門, 平川侑: “Analysis on building envelope and building service equipment design specification using the input and output data from the calculation program to confirm compliance with building energy code (part 1): Identification of the design specification for newly built offices in Japan according to the evaluation result of the building energy code”, 日本建築学会環境系論文集, No. 85, No. 777. pp. 859-869, (2020).
34) 脱炭素社会に向けた住宅・建築物の省エネ対策等のあり方検討会（2021）脱炭素社会に向けた住宅・建築物における省エネ対策等のあり方・進め方(2021), https://www.mlit.go.jp/jutakukentiku/house/content/001419721.pdf

35) 脱炭素社会に向けた住宅・建築物の省エネ対策等のあり方検討会: “住宅・建築物の新築・ストックの省エネ性能別構成割合の試算 ※第６回検討会における委員指摘をふまえ参考掲載” (2021), https://www.mlit.go.jp/jutakukentiku/house/jutakukentiku_house_tk4_000188.html

36) 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 工場等判断基準ワーキンググループ “中間取りまとめ” （2022） https://www.meti.go.jp/shingikai/enecho/shoene_shinene/sho_energy/kojo_handan/pdf/20210323_1.pdf

37) 国土交通省社会資本整備審議会建築分科会 建築環境部会 建築基準制度部会: 今後の住宅・建築物の省エネルギー対策のあり方（第三次報告） 及び建築基準制度のあり方（第四次報告）について 「脱炭素社会の実現に向けた，建築物の省エネ性能の一層の向上， CO2 貯蔵に寄与する建築物における木材の利用促進及び 既存建築ストックの長寿命化の総合的推進に向けて」（2022） https://www.mlit.go.jp/policy/shingikai/house05_sg_000267.html

38) Yamaguchi Y, Shoda Y, Yoshizawa S, Imai T, Perwez U, Shimoda Y, et al. Feasibility assessment of net zero-energy transformation of building stock using integrated synthetic population, building stock, and power distribution network framework. Applied Energy 2023;333:120568. https://doi.org/10.1016/J.APENERGY.2022.120568.

The ITF passenger transport model: Part of the ITF PASTA framework

- Model framework, insights and outputs for the EDITS 'High-with-Low' Scenario

The project has received funding from the Research Institute of Innovative Technology for the Earth (RITE) under subcontract agreement D06710.

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ITF Model Paper

This paper provides insights into the ITF modelling framework that allows for projections of transport demand, and its impacts, up to 2050. Any findings, interpretations and conclusions expressed herein are those of the authors and do not necessarily reflect the views of the International Transport Forum or the OECD. Neither the OECD, ITF nor the authors guarantee the accuracy of any data or other information contained in this publication and accept no responsibility whatsoever for any consequence of their use. This work is published under the responsibility of the Secretary-General of the ITF. This document, as well as any data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

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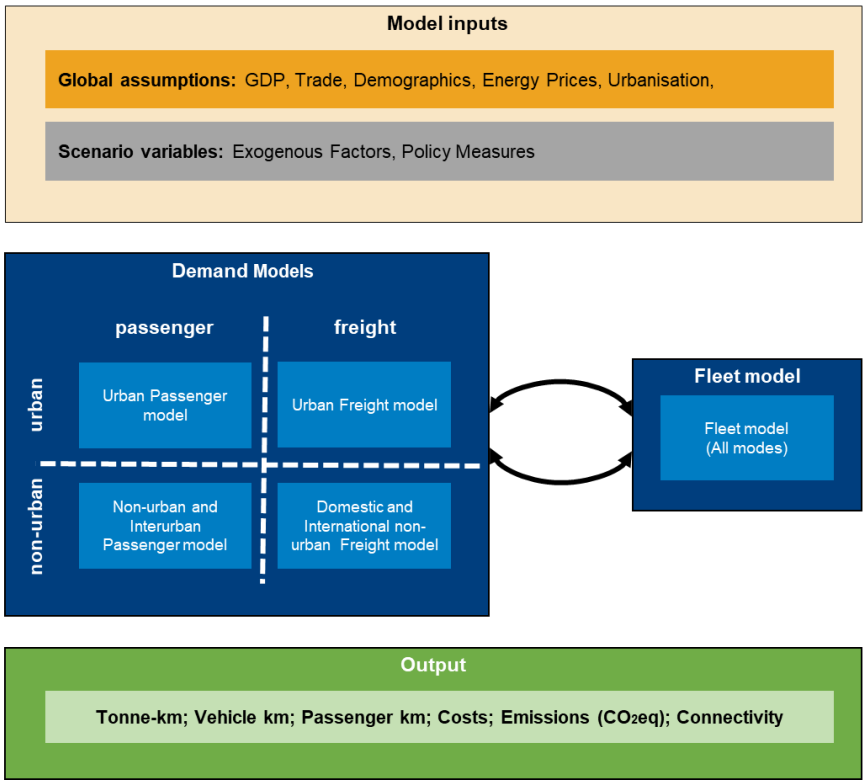
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Introduction

This report describes the two ITF's passenger models: the urban passenger transport model and the non-urban passenger transport model. It also presents results under the EDITS 'High-with-Low' scenario. This global scenario assesses the potential to deliver high wellbeing with low resource consumption.

The urban passenger and the non-urban passenger models are two of the five models that make up the ITF Policy Ambitions and Sustainable Transport Assessment (PASTA) framework. The PASTA framework includes a non-urban (international) freight model, an urban freight model, a non-urban passenger model, and an urban passenger model. It also includes a fleet model that links to the technology development sector and allows for assessing the associated emissions of the transport activity estimated in the other four models.

Figure 1. Simplified ITF PASTA framework



The report first includes information on the models set-up, the methodologies applied in the different model components, and the most relevant data inputs. The report also shows how a Low Demand Scenario (LED), under a 'High-with-Low' narrative was implemented in the Global North and Global South. Finally, the last section of the report analyses the results obtained from the ITF Current Ambition scenario and two variations of the 'High-with-Low' scenario. A first scenario meeting the High-with-low criteria, but without additional pricing measures as per the Current Ambition scenario, and a second adding pricing policies. The report is part of a series describing ITF's transport models covering the global freight and passenger sectors.

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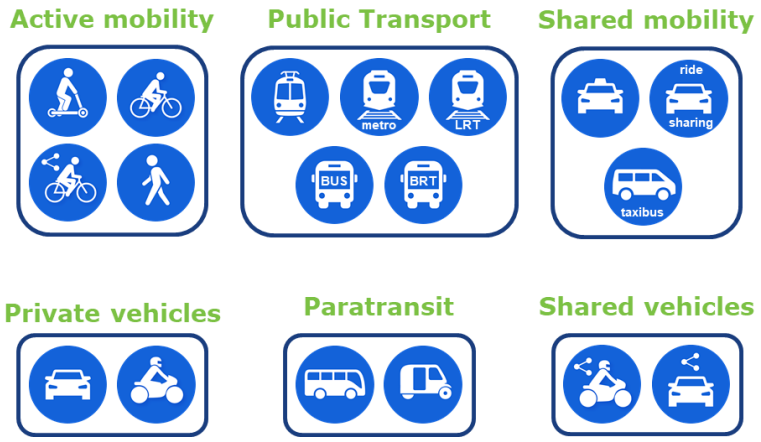
Urban Passenger: Model overview

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 CO_2 and pollutant emissions and alternative 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 to form one of the most extensive databases on global city mobility to account for 18 transport modes (Figure 2) ranging from the conventional private car and public transport to new alternative modes such as shared mobility. These 18 modes can be categorised into: Active mobility, Public Transport, Shared mobility, Private vehicles, Paratransit and Shared vehicles.

The urban passenger model represents travel behaviour by modelling aggregate travel behaviour by traveller segment, depending on the socio-economic characteristics of the respective segment. While the model is built at the FUA level, but the overall mobility patterns are standardised across 19 modelling regions (Figure 3). The model is entirely developed by the ITF and does not rely on any commercial mobility modelling software.

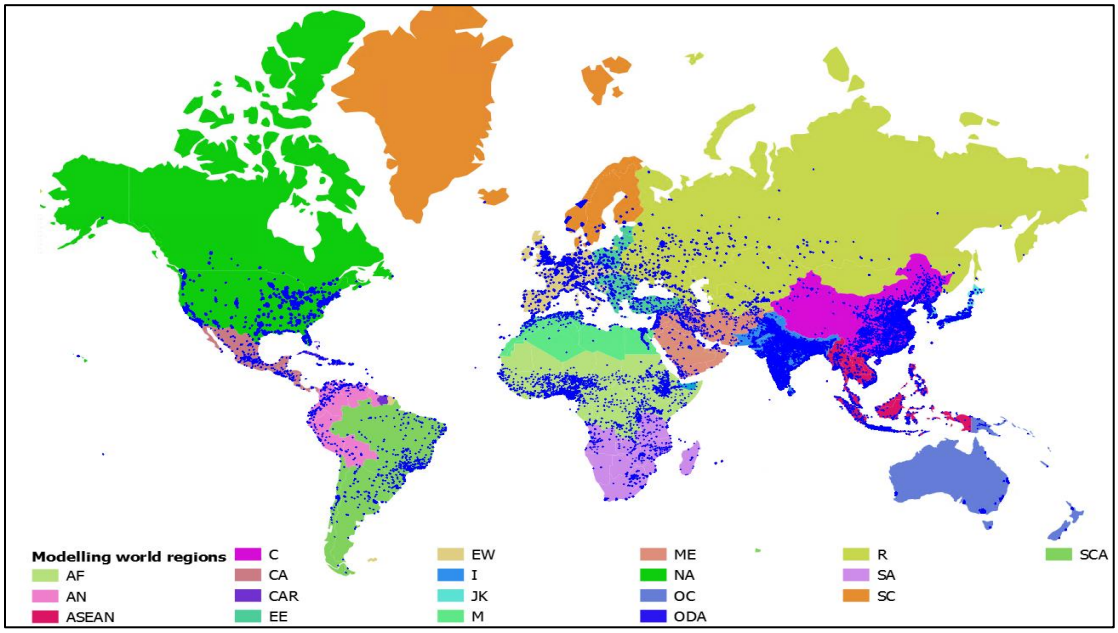
Figure 2 Mobility modes considered in the ITF Urban passenger model



Source: ITF.

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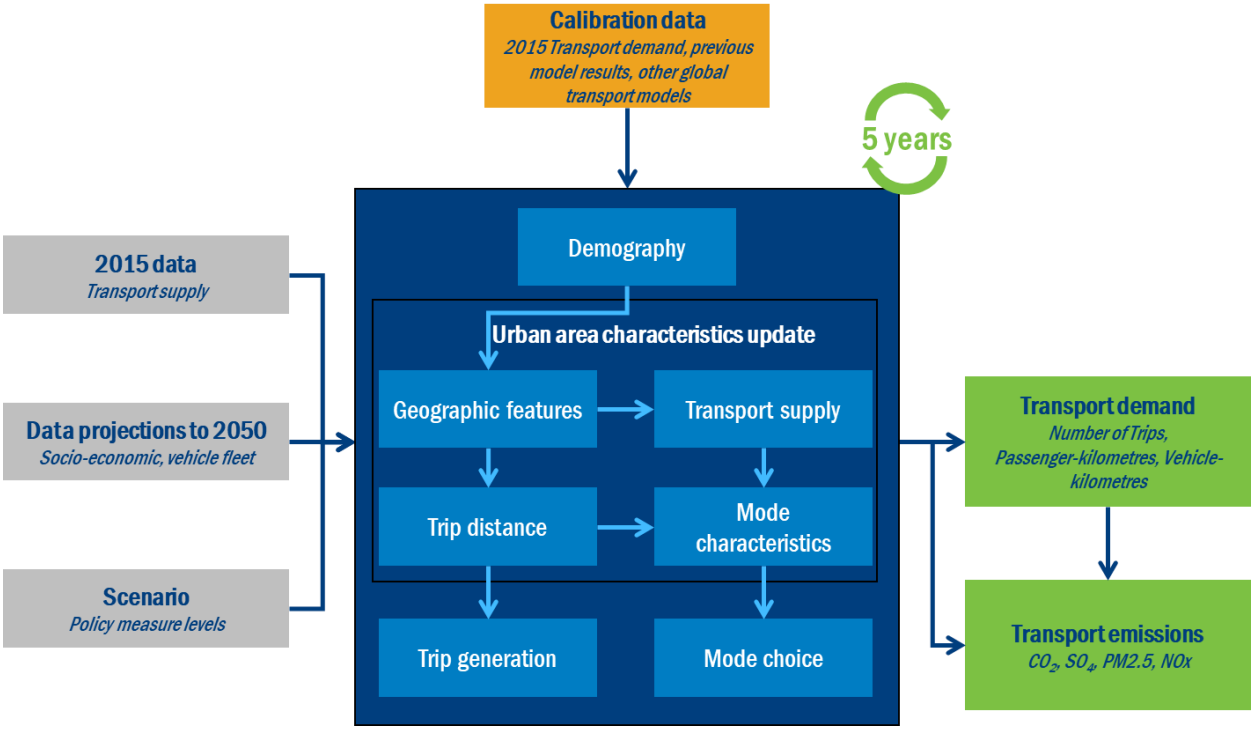
Figure 3 Modelling regions and location of Functional Urban Areas



Source: ITF.

Model components

Figure 4 Structure of the ITF Global Urban Passenger Transport Model 2020



Source: ITF.

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The ITF global urban passenger model is organised around several blocks represented in Error! Reference source not found.: 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.

- 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

$$pop_{80+,g,t+1}{}^{MFUA} = pop_{75-79,g,t}{}^{MFUA} \times \left(1 - dr_{75-79,g,t}{}^{country}\right) + pop_{80+,g,t}{}^{MFUA} \times \left(1 - dr_{80+,g,t}{}^{country}\right) + mig_{a,g,t}{}^{national,MFUA} + mig_{a,g,t}{}^{international,MFUA}$$

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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 1 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.

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Table 1 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

$$U_m{}^{a,g,d,MFUA} = ASC_m^{g,market} + \lambda_{m,r}^{market} \times r_m^{MFUA} + \lambda_{m,access}^{market} \times access_m{}^{MFUA} + \lambda_{m,wait}^{market} \times wait_m^{MFUA} + \lambda_{m,time}^{market} \times time_m^{a,d,MFUA} + \lambda_{m,tr}^{market} \times tr_m^{MFUA} + \lambda_{m,pk}^{market} \times pk_m^{MFUA} + \lambda_{m,cost}^{market} \times cost_m^{d,MFUA} + \lambda_{m,infra}^{market} \times infra_m^{MFUA}$$

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.

- Finally, 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, passenger-kilometre and vehicle-kilometres volumes for each population category, distance category, mode, and 5-year step iteration.

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Model 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 3.

Socio-economic data

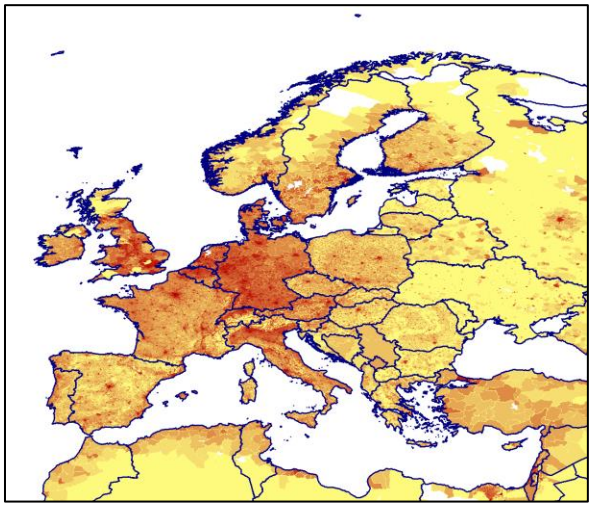
In the ITF global urban passenger model, urban population characteristics are mostly condensed into demographic and economic attributes. The demographic data required is disaggregated at the age (18 age groups: below 1, 1 to 4, 5 to 9… 75 to 79, 80 and over) and gender (female or male) level for each 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 2022[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 distribution of GDP (Nordhaus and Chen, 2016). An example of the GDP distribution is displayed in Figure 5.

[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 2022,https://population.un.org/wpp/

Figure 5 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 Figure 2 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.

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 ITF Vehicle Fleet model of the International Energy Agency (IEA). The emission factors of local pollutants (e.g. BC, CO, NH_3, Nox, Pm_{se}, SO_2, VOC) by mode and fuel type come from the ICCT Transport Roadmap Model[7]. They enable converting travel demand into related emissions, and also have some impact on the modal characteristics.

[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

[7] ICCT (2019), Transportation Roadmap, https://www.theicct.org/transportation-roadmap (accessed on 13 March 2019).

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Non Urban Passenger: Model overview

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 CO_2 emissions on all major transport modes 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 and hydrogen aircrafts, autonomous vehicles, etc.).

The combined non-urban passenger model was initially created for the 2019 ITF Transport Outlook (ITF, 2019). The model structure comprises several sub-models (or modules) that estimate the non-urban passenger transport activity and its effects on the environment in various steps. The model is entirely developed by the ITF and does not rely on any commercial transport modelling software. The current version of the model estimates passenger activity for five transport modes: air, rail, car, bus and moto. The underlying network contains 1191 centroids, where passenger intercity trips start and end, and 1191 regions, where passenger intra-regional travel takes place. Each of the links of the intercity network is described by several attributes. These include mode, distance, frequency, travel time, travel cost (per pkm).

Model components

The model consists of the multiple model components/modules. Most components are interrelated while some others work in parallel. There are two main demand modelling paths, one for intra-regional transport and one for intercity transport.

The modelling component that creates spatial discretisation:

- A **spatial discretisation model** to generate world passenger centroids and regions.

The modelling components that create and modify model inputs:

- A **global network evolution model** based on air routes and surface mode links;
- A **travel price model**.

Intercity travel demand modelling components:

- **Travel activity generation model;**
- **Destination choice model**;
- **Mode choice models;**
- **Route choice model** for intercity aviation.
-

Intra-regional travel demand modelling components:

- **Travel activity generation model;**
- **Mode choice models.**

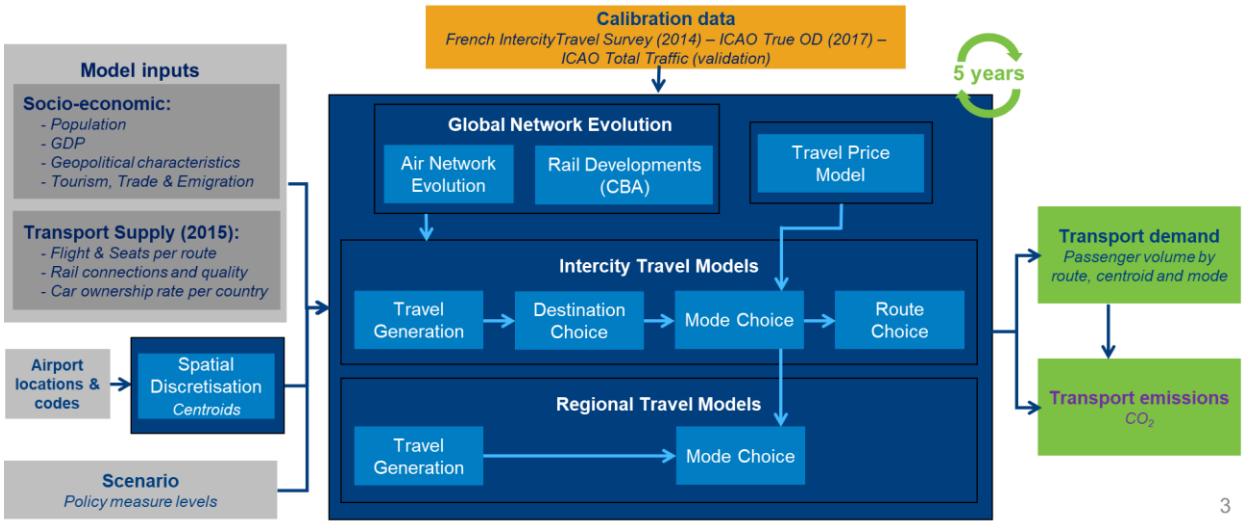
Once all the components are set, the model is computed sequentially as presented in Figure 6. The non-urban passenger model runs in 5-year intervals and makes scenario forecasts until 2050. In this timeframe, several elements of the global network may change. The air network evolves over time either by additional direct links, updating the frequency of flights on links, or by adding low-cost carriers (LCC) to an existing or new connection.

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Surface modes may benefit from increased infrastructure availability or frequency improvements. The high speed rail network (HSR) evolves over time by expanding the network to potential (further) connections.

The cost of travelling of each of the transport modes may also change over time. It depends on expected technological and societal changes (e.g. autonomous vehicles, electric mobility, and shared mobility) but also on the introduction of carbon pricing, carbon offset policies or fuel prices. All such changes would alter the cost of travelling which may impact the propensity to travel and mode choice. The impact of such technological and societal changes can be assessed in the model via scenario analysis by changing the level with which the policy measures are implemented.

Figure 6: Non-urban passenger model scheme



Model inputs

The data inputs for the model can be split in two main categories: socio-economic and geopolitical data, and transport infrastructure and supply data. Transport infrastructure and supply can be further broken down into the intra-regional and intercity level data inputs. Data inputs feed into the model in its various components.

The first category of data inputs is the socio-economic and geopolitical data. These data are used in multiple components of the model:

- ***Population*** estimates and forecasts at the city and region level: The population levels of each city representing a zone as a centroid and the accompanying region are used to estimate travel activity within the generation models. Population levels of each city are also used as an attraction variable in the destination choice model.
- ***Gross Domestic Product (GDP)*** estimates and forecasts at the city-centroid and region level: Similarly to the population estimates, GDP values are estimated for both the city-centroid and the region level. GDP is an important variable for the travel activity generation models and the destination choice model.
- **Geopolitical characteristics** of the city-centroid or the region: Geopolitical variables often play a key role in the non-urban transport activity. Travellers to ***islands*** often rely mainly on air to reach them. Therefore, they have a disproportional mode share by air compared to their size. ***Capitals*** also attract

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more transport activity from other cities of comparable size. Both variables are included as inputs to the model, feeding into the travel activity generation and destination choice models.

- ***Tourism*** estimates are a variable that is complimentary to population. Tourism arrival estimates are taken from official statistics and disaggregated at the city-centroid level. Areas with high tourism activity have more non-urban activity compared with similarly sized cities. Tourism is used in the travel generation model.
- ***Trade and emigration*** estimates between countries: Trade relations between countries influence the amount of people traveling from one to another for business purposes. Emigration has a similar effect in terms of personal/leisure travel. These variables feed into the destination choice model. Urbanisation rates and locations of urban areas are also used at the city-centroid and region level. Regions where the city has a higher share of the total population have higher travel activity. This variable is therefore used in the travel generation model.

Data on transport infrastructure and supply at the intercity level is mainly used to create the global intercity transport network.

- The location and names/codes of ***airports*** are vital for the model. They serve as the basis of the city-centroids. They also connect with flight information that is used to create the global network.
- ***Flight information*** includes all scheduled and non-scheduled flights that happen at an annual basis between all airports. The inputs used include ***the number of flights and seats*** between all airports with additional information on the airlines and the types of planes used. They are aggregated at the route level for computation simplicity. This information is used in most components of the model: travel activity generation, destination choice, mode choice, route choice, and CO_2 intensities.
- ***Availability of rail*** as mode for intercity travel depends on the available infrastructure. Information regarding the presence and the quality of rail connections is used to feed the global transport network component of the model. Quality of rail corresponds to the frequency of service and the type of service in terms of speed, distinguishing slow (<100 km per hour), fast (<200 km per hour), and high speed (>200 km per hour). This information is also essential for many model components.

Information on transport infrastructure and supply at the intra-regional level is also used to inform the activity that happens intra-regionally. For this, data inputs include the presence or not of ***rail infrastructure*** (to determine whether rail travel happens in that region) and the ***car ownership rate*** of the country. These inputs are used in the intra-regional travel activity generation and the intra-regional mode choice models.

Access modes to rail terminals or airports within the region are not considered in the model. It is assumed that if a rail connection exists between two cities or within a region, rail terminals will exist in these locations.

Model outputs

The model provides results at the origin-destination (OD) pair level by mode and (in the case of air) route, for each 5-year model iteration from 2015 (the base year) to 2050. The main outputs are the number of passengers, passenger kilometres and the related CO_2 emissions of non-urban travel activity. Information regarding transfer locations (for air only) is also provided. While results for rail, car, bus and motorcycle are provided per OD pair, results for air are further split onto different routes for each OD pair. For example, between Paris and Barcelona for 2020 one result entry is generated for each of car, bus, moto and rail. It provides information about the number of passengers, passenger kilometres and CO_2 emissions for each. Multiple result entries are provided for travel by air, as one can travel between Paris and Barcelona directly, or transfer in other European cities such as Madrid. Each entry includes the aforementioned outputs and the city where the transfer is done.

The model also provides results for intra-regional transport activity in a similar format. Intra-regional trips can, however, only be done by rail, car, moto and bus.

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Results can be aggregated at a centroid, country, or any larger geographical level. They can also be grouped by origin or destination, estimating the total passengers leaving an origin or arriving at a destination.

Detailed model component descriptions

This section provides information on the methodologies applied in the different model components work.

Spatial discretisation model (centroids and regions)

This model defines the regions that are used to estimate transport flows between or within the regions. Regions are based on the location of airports. More specifically, each region is represented by a centroid and an influence area around the centroid. The centroids are defined by all large and medium sized airports with international operating codes as classified by IATA (2019).They are clustered by city airport codes where several airports exist in the same city or where airports are within 100 km of the main airport and within the same country. This results in a total of 1191 centroids (Africa (118), Asia (107), China + India (76), EEA + Turkey (320), Latin America (171), Middle East (27), North America (216), OECD Pacific (75), Transition countries (81)). The name of the respective airport or city code designates each centroid. The influence areas around the centroid are defined by the use of a raster-based world surface map. Each raster cell is assigned to a centroid based on its distance from the centroid and considering country borders. Each centroid is characterised by population and GDP indicators. To obtain estimates for these indicators, the raster cells are linked to raster-based global (CIESIN- Columbia University, 2018) and raster based GDP estimates (Kummu et al., 2018).

Global intercity transport network model

This model component creates a transport network between the 1191 centroids to accommodate intercity travel activity and determines the evolution of the global network over time. In the model, intercity travel can be done by five different modes (air, rail, car, bus and motorcycle). A connection between two centroids may exist for one or more modes.

A connection between two centroids is assumed to be possible **by road** (for car, bus and motorcycle) if there is a continuous surface transport connection, and if the Euclidian distance is less than 2000 km (or 3000 km in case both centroids are in the same country).

A **rail** connection is assumed to exist in 2015 if rail infrastructure connecting the respective two centroids exists in reality.

For connections by **air**, a different approach is taken. Information on all international and domestic flights for 2015 (obtained from the Innovata Schedules Reference Service database) is aggregated at the OD pair level. If all city-centroids were connected by air, that would amount to a total of 1 417 290 air links. According to the flight data from 2015, only 28 137 (2%) of those links were served by direct flights. However, in reality people also travel between cities that do not have direct flight connection, by making transfers. Therefore, to realistically represent the actual air network, an algorithm estimates indirect routes with up to two connections. This exercise increases the total number of air links in 2015 to 230 095. This number includes both direct and indirect links and amounts to 16% of all possible links. The frequency of an indirect route is set to be the minimum of the frequencies of the each connection on that route. The waiting time at a transfer airport is defined by the frequency of the inward and outward flights. Surface modes can also serve as feeders for aviation. For example, someone travelling from the centroid of Lyon (France) to Los Angeles (USA) can go to Paris by train or road and then take the plane to Los Angeles. This exercise brings the total number of all “air” links in 2015 (direct air links, indirect air links, or indirect links with surface feeder modes) to 987 127. This number represents 70% of all possible links between OD pairs. 75% of the total intercity travel demand is, however, met by “air-only” connections (whether direct or indirect).

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The global network evolves over time either by including additional direct links or by improving the existent connections. Surface road modes may benefit from increased infrastructure availability or from improvements with regards to the capacity of and/or speed limits on the network.

The main changes for rail accounted for in the model are potential (further) developments of the high speed rail network (HSR) over time. A simple cost-benefit analysis (CBA) explores whether the demand generated or shifted to a HSR due to travel time savings would outweigh the high fixed costs and make the Net Present Value of the project greater than 0 or not. The following variables are considered in the CBA: fixed cost, maintenance cost and operation cost as cost items; generated traffic, time-savings and reduced negative externalities from other modes as benefits. For the financial assessment, the following assumptions are made:

- All capital expenditure costs occur before the operation of the transportation lines;
- An annual discount rate of 5%;
- Consistent, annual maintenance and operation costs;
- No asset renewal;
- Ticket price grows the same pace as the GDP per capita, independent of journey type.

The development plans are estimated exogenously to the main model in this simple CBA and inputted into the main model. As the model considers the update of routes for OD pairs and the presence of intermodal solutions, the new services are integrated dynamically as options.

The main evolution of the air network is assumed to be the addition of new direct links between OD pairs. The module creates new links on the basis of a binomial regression analysis which assesses the likelihood of whether a direct link exits. This likelihood is defined as a function of economic mass (the product of the GDP at the origin and the GDP at the destination of each OD pair), cultural connection and distance. In each iteration, the module may create additional air links or remove existing ones. A link is removed in case the travel demand on the link of the previous iteration did not reach a minimum passenger threshold: 15 000 passengers annually for distances over 3500 km and 45 000 for smaller distances. If both origin and destination are within the same country, these thresholds are lowered by 50%.

The existence (and introduction) of low-cost carriers (LCC) links is also updated at each iteration. A higher economic mass is required for a LCC link to be created. LCC links are constrained to distances of up to 3500 km. A new LCC link starts with an initial share between 2.5% and 10%. This value may grow over time to represent 25% of the market, or more if the prospective demand of the OD pair grows.

The frequency of air connections is updated at each iteration based on the new demand with the use of elasticity values. These are extracted by the Innovata Schedules Reference Service database and are differentiated by two parameters, distance and frequency (in binary terms – high or low). The elasticity values are:

- High frequency (> 2,000 flights/year) and short/medium-haul (<= 3,500 km): 0.6;
- High frequency (> 2,000 flights/year) and long-haul (> 3,500 km): 0.5;
- Low frequency (<= 2,000 flights/year) and short/medium-haul (<= 3,500 km): 0.8;
- Low frequency (<= 2,000 flights/year) and long-haul (> 3,500 km): 0.7.

Travel Price Model

The travel price model estimates travel prices across different modes. Prices are essential to model demand for passenger travel. This is especially the case for air travel where price variations across different airlines and routing options are significant.

The estimation of air travel prices does not include price differentiation across different airlines; price variations between two centroids however do exist by itinerary. The estimation procedure presents a refinement of the

model discussed in (Benezech et al., 2016).The data used to calibrate the airline route price setting module was provided by the operators of the website Skyscanner (www.skyscanner.com). The data provides information on all requests made by the website's users between November 2012 and October 2013 for return economy trips between any of the main airports associated with countries represented in the model. For each request, the dataset contains details on the date of the request, the origin and departure of the trip, the dates of the outbound and inbound legs of the trip, the airline, the price for the return trip, and the number of transfers for outbound and/or inbound trips.

Competition and low-cost carriers have a very significant impact on prices. This impact is strongest for direct flights. The price model does not attempt to realistically explain prices between competitors- this would require airline modelling and game theoretical approaches (Grauberger and Kimms, 2016; Hansen, 1990) . However, the model does attempt to reflect the main impacts of competition levels and low-cost carries on the different routes. The base prices for the model are obtained from the average prices observed in the dataset. The prices are grouped by origin-destination pair differentiated by the number of transfers. Therefore, for a given origin-destination pair, all itineraries with the same number of stops are assumed to have the same price. The other element that plays a role in air travel prices is the effect of frequency and the HH-index (airline concentration indicator by number of offered seats – an indicator of the competition on a route). Itineraries with higher flight frequencies and lower airline concentration (lower HH-index) have lower prices. Finally, the presence of low-cost carriers also influences air travel prices. As observed in the data, origin-destination pairs that are served by low-cost carriers have lower prices compared to origin-destination pairs that are not served by low-cost carriers. Prices differences show to vary little across different itineraries. This difference in prices however, is sufficient to highlight the differences between direct and indirect routes and different competition environments.

Rail travel costs are estimated on a per passenger kilometre basis. Data for rail fares in France are used to compute the cost structure. Prices are indexed for the type of service (slow, fast, and high-speed). The costs are also indexed to the GDP per capita of France, which allows the extrapolation of these costs to the rest of the world. This extrapolation works as follows: The cost of rail fares is estimated in relation to France's GDP per capita. This relation remains steady for all countries. Countries with higher GDP per capita than France will have higher rail travel costs; whereas countries with lower GDP per capita will have lower rail travel costs.

Car and bus travel prices depend on two components. The first component is the price of gasoline in a country (relevant time series data including forecasts stem from the IEA (2019). The second component is a fixed price component that depends on distance ranges and reflects toll costs. For both these modes, prices are affected by vehicle load factors, which may change over time. Furthermore, they can be affected by any trends that influence the unit cost of transport (e.g. development of gas prices, automation, etc.).

Price plays an important role in the propensity to travel (i.e. in generation models), mode choice and route choice components.

Passenger transport activity generation model

Transport generation is handled via two different sub-models: one for intercity travel and one for intra-regional travel. Both these sub-models are Poisson models. A Poisson model is a generalised linear regression model where the link function (the relation between the estimated value and the expected value) follows the Poisson distribution.

The inter-city demand generation sub-model has four different formulations – one for each type of inter-city travel: domestic trip, international trip without border controls (e.g. Schengen zone, US-Canada), short and medium haul international trips (less than 4 hours flight time), and long haul international trips (more than 4 hours flight time). The model estimates how many trips will be generated by a region (a city and the surrounding region) for each of the four types of intercity travel. The main variable affecting this is the sum of the population of the region and the number of tourist visitors in that region. Tourists generate about half of the intercity travel activity of inhabitants. This means that a region with two million inhabitants and one million tourists will have

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the same intercity travel activity generation as a region with 2.5 million inhabitants, all other variables being equal. Next to population and tourists, the economic activity of the centroid, expressed in GDP per capita, is one of the most influential explanatory variables, especially in the long-haul segment. The variable ratio between the regional population and the city population also influences demand generation: a high ratio signifies a region where the population is evenly spread across the region, while a low ratio typically identifies a big city. This ratio therefore has a negative effect on travel generation for long haul travel, i.e. as the ratio decreases (the city becoming bigger), the demand for long haul travel increases. This is because big cities attract/generate more travel demand from/to faraway destinations. Being an island is positively correlated with inter-city travel demand, with the exception of international short- and medium-haul travel where it is strongly negative. Very few cases of islands fall in the short- and medium-haul segment for reaching destinations, which explains this fact. On the other hand, being a capital positively influences travel demand for international travel. It has a rather weak effect when it comes to domestic or no border control travel segments. Transport connectivity variables, such as the presence of high speed rail and the amount of airport throughput, increase activity generation quite significantly for most travel segments.

The output of this sub-model is the number of trips that each region generates for each of the four segments of intercity travel. These can be described as the propensity to travel segments for each centroid.

The intra-**regional generation sub-model** has a simpler configuration. Little information exists on the number of trips that are done within regions. Therefore, the results are aggregated on a country level. The model uses non-urban population, GDP per capita and the size of the country as explanatory variables. GDP per capita defines transport costs and how these costs evolve over time. The transport costs are indexed to the 2015 value. The results are validated on the country level where data is available by subtracting urban activity as estimated by the ITF Urban Passenger Model (ITF, 2020) from the total. The estimated model is given by:

$$Regional\ surface\ pkm_{\ i} = rural\ pop_i \cdot \left(\frac{0.004 \cdot \ln(Equivalent\ area_i + 0.027}{1 + e^{10.5116 - 1.823 \cdot GDP\ capita\ available_i}}\right) \quad (1)$$

$$GDP\ capita\ available_i = GDP\ capita_i \cdot \text{Transport costs (indexed to 2015)} \quad (2)$$

When forecasting trip generation for the study period, socio economic information is updated based on the economic and population forecasts of the UN-DESA (2022) and GDP data for regions (OECD, 2022). Transport supply variables are updated based on the model results of the previous year.

Destination choice model

The destination choice model allocates the trips of each destination segment to the different destinations. The destination choice component only applies for the intercity non-urban travel. The intercity travel generation model generates activity for four destination segments. The destination choice model distributes this activity across the different destinations in each segment. A discrete choice sub-model with a non-linear utility function is used. The utility function for this model contains multiple variables. These are socioeconomic variables (population – pop, trade – T, and emigration – E), geopolitical and cultural variables (use of same language – L, being a capitol – C, and being an island – I), and transport services provision for each OD pair (road highway connection – Rh, rail travel time – Rc, frequency of services of high speed rail services – HSR, direct daily flight frequency – FF, availability of low cost carriers – LCC, and air travel time – TTair). The probability *P* of travelling an origin-destination (OD) pair is then multiplied by the total number of trips originating from a centroid to derive a centroids pairs OD matrix. The model equation is:

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$$V_{Oi} = (C_i \cdot \alpha_0 + I_i \cdot \alpha_1) \cdot (FF_{Oi} \cdot \alpha_2 + HSR_{Oi} \cdot \alpha_3) \cdot (T_{Oi} \cdot \alpha_4 + pop_{Oi} \cdot \alpha_5 + E_{Oi} \cdot \alpha_6) \cdot (Rf_{Oi} \cdot \alpha_7 + Rh_{Oi} \cdot \alpha_8 + LCC_{Oi} \cdot \alpha_9 + L_{Oi} \cdot \alpha_{10}) \cdot e^{TTair_{Oi} \cdot \alpha_{11}} \quad (3)$$

$$P_{Oi} = \frac{e^{Sc \cdot V_{Oi}}}{\sum_{j \in D} e^{Sc \cdot V_{Oj}}} \quad (4)$$

where *o* is the origin and *i* the destinations.

As in the trip generation model, socioeconomic variables are the most impactful. Population of the destination region and the trade relation between the origin and destination regions are the two most impactful elements of attraction, regardless of the travel segment. Other socioeconomic variables such as same language and emigration relations are also significant predictors of travel flows between regions. Similar to the generation model, capital cities are much more important in the long-haul travel segment. Regions with higher levels of transport connectivity have a higher attractiveness as a destination, particularly in terms of daily flight and high-speed rail frequencies. Finally, distance, measured by the travel time of a direct flight, is a negative factor. Its importance increases with travel distance (i.e. it has more impact for destination choice in the long haul segment, than in the short haul segment).

Mode choice models

Two mode choice sub-models distribute the flows between and within regions across the different modes. In both cases, this is done by a discrete choice model. For intercity travel, five mode alternatives are available, car, moto, bus, rail, and air. Air is not available for intra-regional travel. In both sub-models, the availability of rail depends on the actual rail infrastructure that is in place (or assumed to be in place in the future). Both models are multinomial logit models.

The utility function includes regional mode preferences (panel terms), specific attributes of the best route that represents the mode (price, travel time and number of transfers) and indicators of connectivity that highlight the role of frequent connections and reliability in intercity mode choice. The most interesting results from the intercity mode choice sub-model are the differences between the regions in the panel terms and the variables. North America has a high positive panel term for car and air travel, which can be associated with the driving culture and the high distances involved respectively. China, on the other hand, has a positive panel term for bus and a negative one for air, whereas India and Russia have a positive panel term for rail travel. Finally, in Europe, the highly developed rail network and the ease of travelling within the Schengen zone gives positive panel terms for rail and air travel and negative ones for bus and car. The other variables such as price, travel time, and the number of transfers are all significant and negatively impact the choice of each mode, while flight frequency and high speed rail frequency are positive for air and rail respectively.

The intra-regional sub-model uses fewer variables in the utility functions. These are GDP per capita, car ownership rate, rail infrastructure availability and a panel term by region for rail. Car is the natural preference, whereas rail gets a boost by higher levels of rail infrastructure. Finally, bus has a negative relation with GDP per capita (as GDP increases, preferences shift from bus to car).

Route choice model for aviation

The route choice model allocates passengers on the different possible itineraries for each origin-destination pair. This model is implemented only for travel by air within intercity travel to incorporate the use of different flight routes. Road, rail and bus, on the other hand, are assigned to the shortest path between each OD pair.

The final route choice model for aviation has a nested structure based on the number of required stops for the itinerary. The variables in the utility function for each route are travel time (including the estimated transfer time), price, frequency, and a transfer penalty. A Box-Cox transformation is applied to travel time to account for the varying impact of travel time savings that depend on the base travel time. For example, a travel time saving

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of 1 hour is more relevant if the total duration of the trip is 3 hours rather than 10 hours. The generated routes are limited to three legs, while each of them is characterised by a quality of service index. This index takes into account the various characteristics of each route: travel time, frequency, and transfer time. In an improvement from the pre-existing international aviation model, air travel can also use surface modes as feeders. For example, a traveller might travel by road or rail to a centroid nearby and then fly to their destination. This feeder mode is counted as one of the possible three legs that are allowed for in the route choice model for aviation.

Calculation of the outputs

The model provides passenger-kilometres (pkm) and vehicle-kilometres (vkm) for each OD pair and centroid, disaggregated by transport mode. These outputs can be further aggregated at country and regional levels.

CO_2 emissions by mode are estimated via transport activity expressed in either pkm or vkm, depending on the mode. For road transport (car, moto and bus), CO_2 is estimated via vkm, assuming vehicle load factors (to get from pkm to vkm) defined by:

$$\begin{aligned} car\ load\ factor_{\ ij} &= \min(4, 1.306 \cdot (1 - \%SM_{ij}) + 0.0006 \cdot distance_{ij} \\ &\quad + 2.800 \cdot \%SM_{ij} + 0.101 \cdot \%Saut_{ij} \end{aligned} \tag{5}$$

$$bus\ load\ factor_{ij} = \min(50, 22.544 + 0.006 \cdot distance_{ij}) \tag{6}$$

These load factors are estimated on data stemming from ITF member countries and depend on the average distance driven and the effect of potential organisational or technological disruptive elements. These are shared mobility (identified as SM in equation 5) and automation (identified as Saut in equation 5). For other modes, CO_2 estimates are estimated via transport activity in pkm.

CO_2 intensities per vkm (for bus, moto and car) and pkm (for rail and air) and the future development of these CO_2 intensities for the different modes are calculated within the framework of the in-house fleet model.

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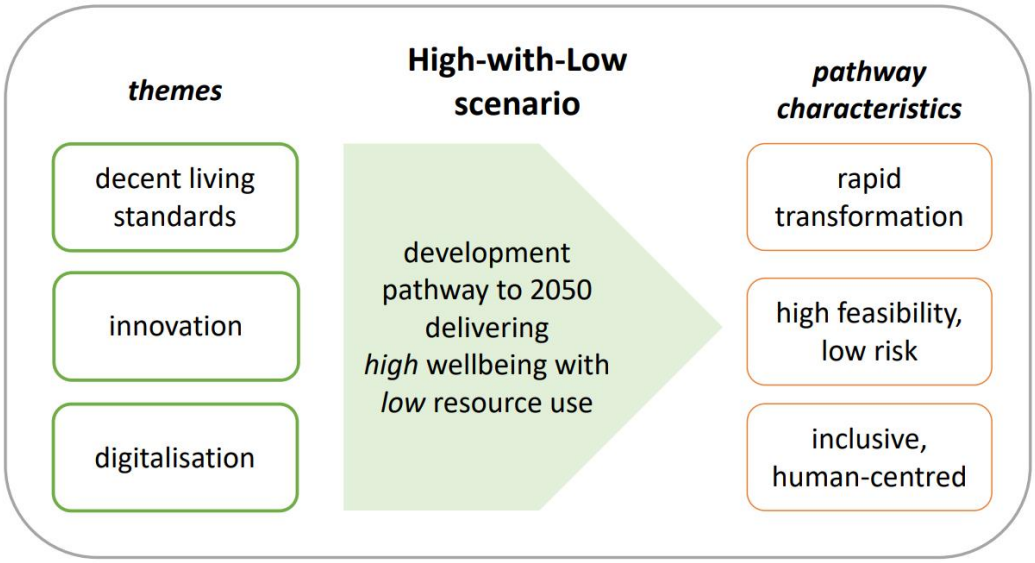
Implementing 'High-with-Low' scenarios

The ITF models were designed and further updated to estimate and evaluate the impact of policy measures on transport activity and related emissions under the 'High-with-Low' scenarios.

The *Current Ambition* scenario builds on existing policies and commitments to estimate the current pathways of transport demand and related emissions. It was built by the ITF in 2020 for the preparation of the ITF Transport Outlook 2021 (ITF, 2021), and adjusted for the forthcoming ITF Transport Outlook 2023 since. It is the result of an international survey on current transport policies and technology development implementation all over the world, filled by many experts in the ITF network.

The *High-with-low* scenario narrative has been designed by the EDITS research network and described in-depth in Grubler et al. (2022). This *High-with-low* scenario achieves high levels of human wellbeing that are more equitably distributed globally with drastically reduced energy and material consumption compared to today, as opposed to the *Current Ambition* scenario representing the current pathways existing policies and developments are leading us too. High-with-low relies on three main themes displayed in Figure 7.

Figure 7 Main themes and characteristics of the development pathways to 2050 of the 'High-with-Low' scenario, from (Grubler et al., 2022).



For this study, the *High-with-low* scenario is segmented into two separate scenarios. *High-with-low without pricing* is a first scenario meeting the *High-with-low* criteria, but without additional pricing measures as per the *Current Ambition* scenario. It represents a *High-with-low* scenario where individuals are not financially penalised for reaching climate objectives. *High-with-low with pricing* includes pricing policies (i.e. carbon pricing, road pricing, parking pricing, air ticket taxes). The specific measures boosted in the *High-with-low with pricing* scenario are highlighted in the measure tables and identified with an asterisk. Their *High-with-low without pricing* scenario level of implementation correspond to the level of implementation of the Current Ambition scenario of the forthcoming ITF Transport Outlook 2023. It should also be noted that these pricing measures are higher for richer countries, namely the Global North and China.

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All assumptions regarding the technology development, vehicle fleet composition and fuel efficiencies are external and correspond to the High Ambition scenario of the forthcoming ITF Transport Outlook 2023.

Table 2 shows measures implemented in the Urban Passenger Model and Table 3 shows measures implemented in the Non-Urban Passenger Model with target values for Global North and Global South by 2050.

Table 2 List of measures for urban passenger transport and their 2050 targets implemented in the model

Policy measures	Description	'High-with-Low w/ Pricing'	
		Global North	Global South
Carbon pricing*	Pricing of carbon-based fuels based on the emissions they produce	750 USD/ tonne CO_2	300 USD/ tonne CO_2
Parking pricing and restrictions*	Regulations to control availability and price of parking spaces for motorised vehicles	30-225% fare increase	40-75% fare increase
Road pricing*	Charges applied to motorised vehicles for the use of road infrastructure	2.5-25% cost increase	5-10% cost increase
Bike and Pedestrian infrastructure improvements	Increase in dedicated infrastructure for active mobility	40-100% network increase	100-500% network increase
Land-use planning	Densification of cities differentiated between the city centre and the suburbs for cities over 300 000 inhabitants	0-30% density increase	10-40% density increase
Public transport infrastructure improvements	Improvements to public transport network density and size differentiated for cities over and under 1 000 000 inhabitants	0-75% network increase	60-200% network increase
Public transport service improvements	Improvements to public transport service frequency and capacity differentiated for bus and mass transit services	10-50% service increase	10-30% service increase
Integrated public transport ticketing	Integration of public transport ticketing systems	3-7.5% fare decrease	1.5-7.5% fare decrease
Public transport priority and express lanes	Prioritising circulation of public transport vehicles in traffic through signal priority or express lanes	10-75% network prioritised	20-60% network prioritised
Transit-Oriented Development (TOD)	Increase in mixed-use development in neighbourhoods around public transport hubs	9.5% land-use diversity increase	7.5% land-use diversity increase

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Teleworking	Policies favouring and trends regarding the practice of home office	10-40% of active population teleworking	3.5-9% of active population teleworking
Urban vehicle restriction scheme	Car restriction policies in certain areas and during certain times to limit congestion. Typically applied in the city centre	10-31.5% of vehicles restricted from circulated in centre	3.5-15% of vehicles restricted from circulated in centre
Speed limitations	Traffic calming measure to reduce speed and dominance of motor vehicles through low-speed zones or infrastructure	12.5-50% speed decrease	5-50% of vehicles speed decrease
Carpooling policies	Carpooling policies encourage consolidating private vehicle trips with similar origins and destinations	7.2-16.6% occupancy rate increase	7.6-9% occupancy rate increase
Vehicle sharing incentives	Incentives to encourage car or motorcycle rental schemes where members have access to a pool of vehicles as needed	5-60% shared vehicles per capita increase	5-60% shared vehicles per capita increase
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)	30-90% increase of population covered by a MaaS system	10-20% increase of population covered by a MaaS system
Ride sharing and shared mobility	Increased ridership in non-urban road transport differentiated for car and bus-based services	25-300% ride sharing vehicles per capita increase	50-300% ride sharing vehicles per capita increase

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Table 3 List of measures for non-urban passenger transport and their 2050 targets implemented in the model

Policy measures	Description	'High-with-Low'	
		Global North	Global South
Reduced propensity to fly	Percentage of the population that avoid flying due to climate considerations	20% - 30%	0%
Reduction in business travel due to teleconferencing	Percentage of air trips reduction due to teleconferencing	12.5%	2.5%
Shared mobility	Percentage of shared trips of the total trips by car	30%	20.0%
Carbon pricing (all modes) *	Increases cost of all carbon emitting modes via a carbon tax (USD)	450 – 600 USD/ tonne CO_2e	200 – 300 USD/ tonne CO_2e
Ticket taxes (air travel) *	Increases cost of air travel as a percentage of the air fare	30 – 45%	8 – 25%
Electric vehicles	Increases the uptake of electric vehicles in all modes	ITF High Ambition scenario	
New propulsion aircrafts	Battery electric and hydrogen propelled aircrafts	Battery electric and hydrogen-propelled aircrafts are commercially available and a competitive alternative for short and medium haul travel, respectively.	
Sustainable Aviation Fuel (SAF) mandates	Percentage of the total fuels of aviation required to be SAF	100% to 73% depending on the regions.	
Short hall flight (<500 km) ban	Introduced to encourage the uptake of rail where good quality connections exist	Progressive implementation towards 2050 depending on the region. By 2050, measure implemented in all regions.	
Development high-speed rail (HSR)	Development of high-speed-rail infrastructure between cities where it is economically feasible		
Rail frequency improvement and electrification	Investment in rail and electrification of rail networks	Frequency (50%) and speed (20%) improvements across regions.	

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Assessing 'High-with-Low' scenarios

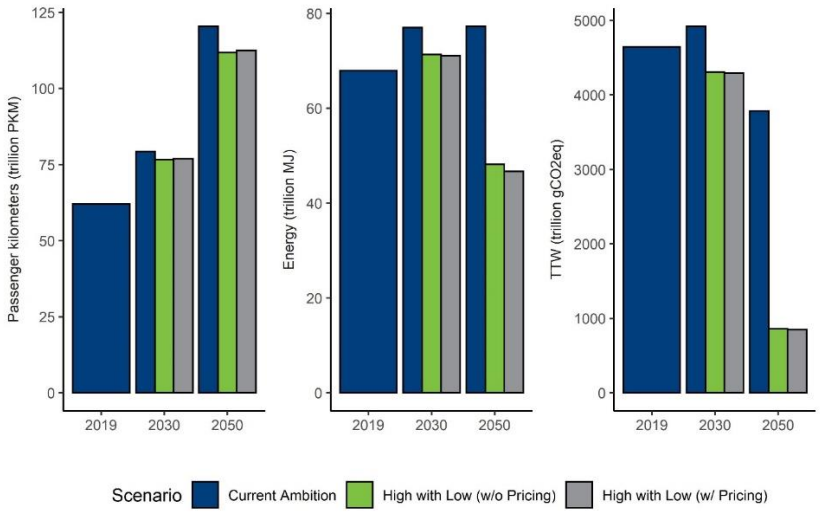
The primary model outputs of the urban and non-urban passenger models are number of passengers, passenger kilometres (pkm), energy, and related CO_2 emissions by origin-destination (OD) pair and mode. The total passenger flows, energy and emissions can be estimated on a specific OD pair, from an origin to all destinations or to a destination from all origins. This level of detail of results allows their aggregation in several ways; total pkm, energy and emissions can be assessed at the global, regional, or country level.

This section presents illustrative outputs of the global passenger models. The results presented stem from the model runs developed to assess the 'High-with-Low' scenario narrative designed by the EDITS research network. The Current Ambition (CA) scenario developed within the forthcoming ITF Outlook 2023 represents a future where current political commitments and reasonable technological developments take place throughout the study period (2019-2050). The 'High-with-Low' scenario represents a more equitable future where energy and material consumption is lower than at present. Two variations of the High-with-low scenario are considered:

- 'High-with-Low w/o Pricing': meets the High-with-Low criteria but without additional pricing measures as per the Current Ambition scenario;
- 'High-with-Low w/ Pricing': meets the High-with-Low criteria implementing pricing measures.

Figure 8 below presents the projected growth of global passenger transport demand, energy and CO_2 emissions to 2030 and 2050, under the Current Ambition and the two High-with-Low scenarios. Both High-with-Low scenarios present similar potential to reduce passenger kilometres, energy and emissions compared to the Current Ambition scenario. Under the High-with-Low scenarios, tailpipe emissions decrease 77% with respect to the Current Ambition while passenger kilometres decrease by 7%. This shows the reduced sensitivity of passenger travel demand to the policy measures implemented within the High-with-Low scenarios, and instead highlights the high impact that technology development (fleet and fuels) has as means to decarbonise passenger transport.

Figure 8: Global passenger-kilometres, energy and tailpipe emissions per scenario



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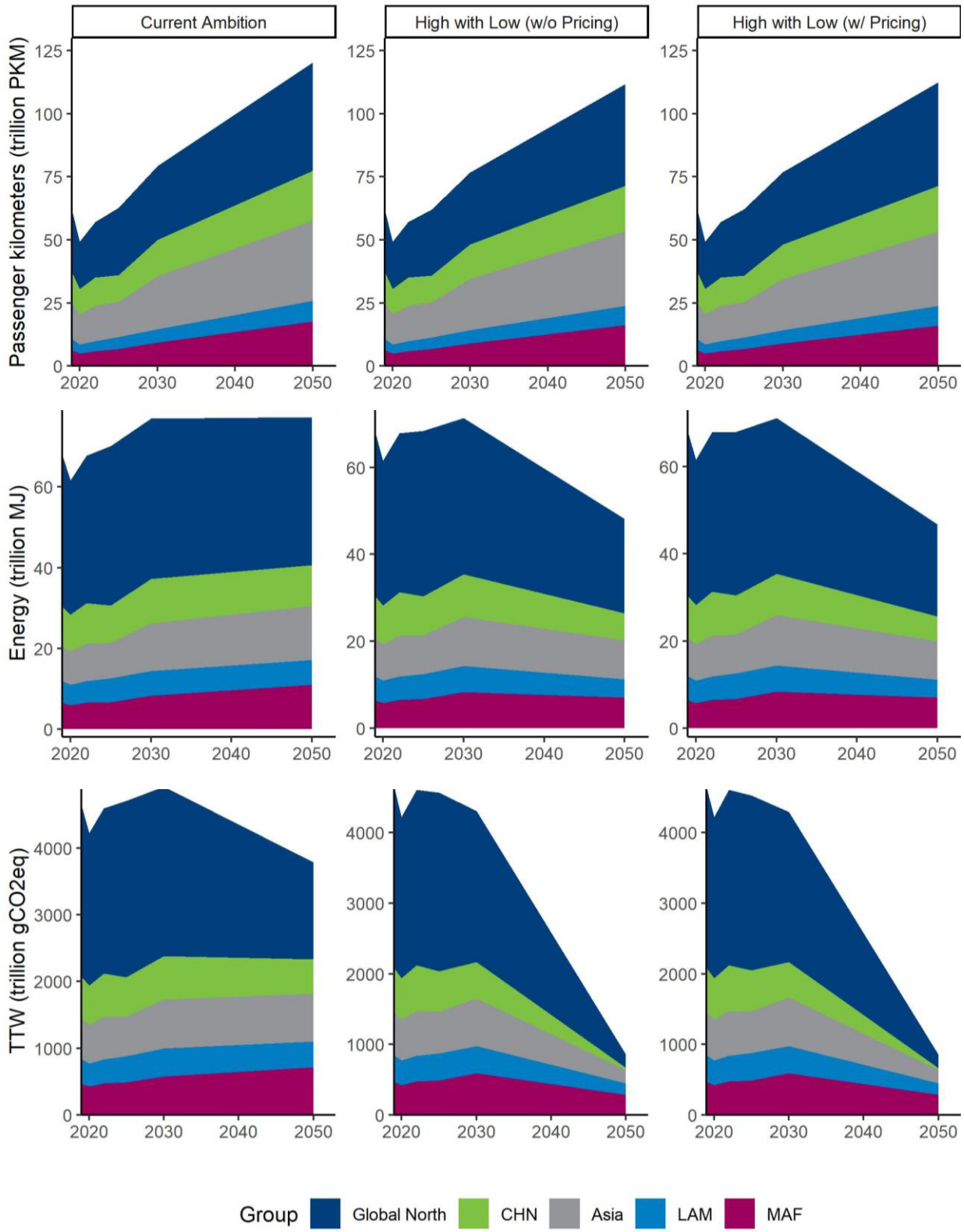
Forecasted global transport activity (pkm) continues to grow in all world regions and under all scenarios (Figure 9). Global demand for passenger travel grows from 62 trillion pkm in 2019 to 120.4 trillion pkm in 2050 under the Current Ambition Scenario and to 112.6 trillion pkm in 2050 under the High-with-Low w/Pricing scenario. Contrarily, energy demand projections plateaus after 2030 under the Current Ambition scenario, while it significantly decrease under both High-with-Low scenarios mainly driven by changes in the Global North. Tailpipe CO_2 emissions outlook shows a decrease in all scenarios. The reduction of emissions under the High-with-Low scenarios is mainly determined by the high level of technology improvements in the Global North and China, and to a lower extent in the Global South (Asia, Latin America and Caribbean, Middle East and Africa).

Further split for the regional groupings (Figure 10) shows that solely in the Global North passenger travel activity decreases when implementing the High-with-Low with pricing measures compared to the High-with-Low without pricing. High-with-Low scenarios estimate by 2050 a reduction of 4% to 9% of passenger kilometres compared to the Current Ambition scenario, depending on the region.

Tailpipe CO_2 emissions by 2050 under the Current Ambition scenario are projected to be lower than in the base year 2019 only in the Global North and China. Instead, under both High-with-Low scenarios all regions reduce the emissions compared to 2019. This reduction varies across regions from 93% in the Global North and China to 56% in the Global South (Asia, Latin America and Caribbean, Middle East and Africa).

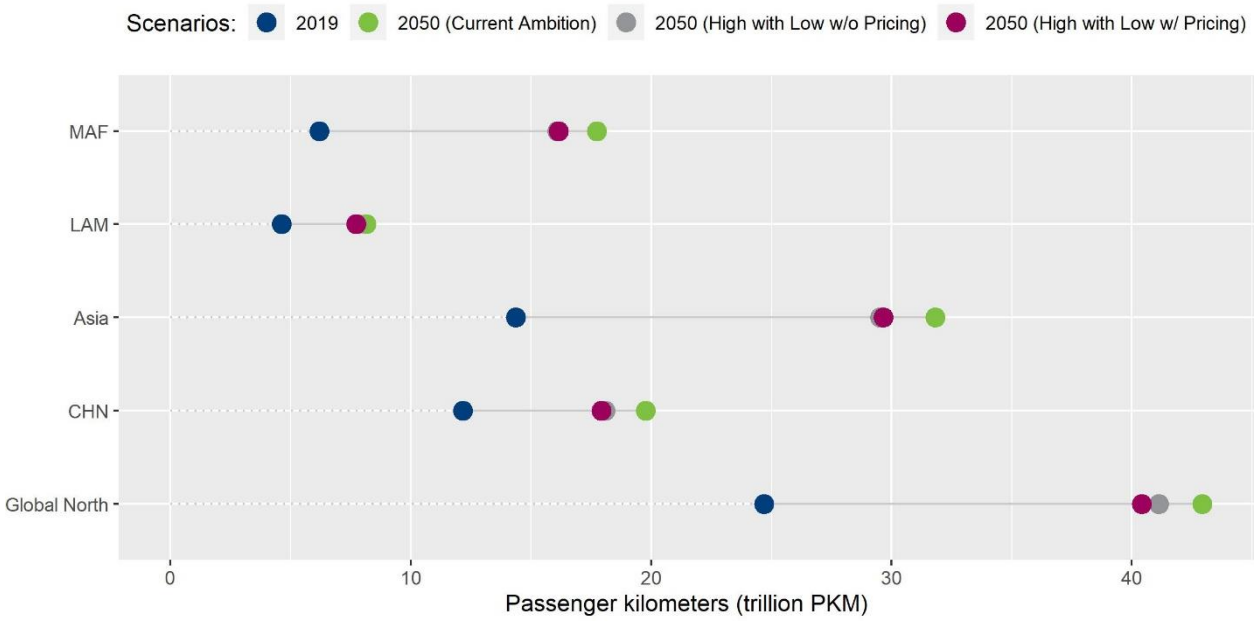
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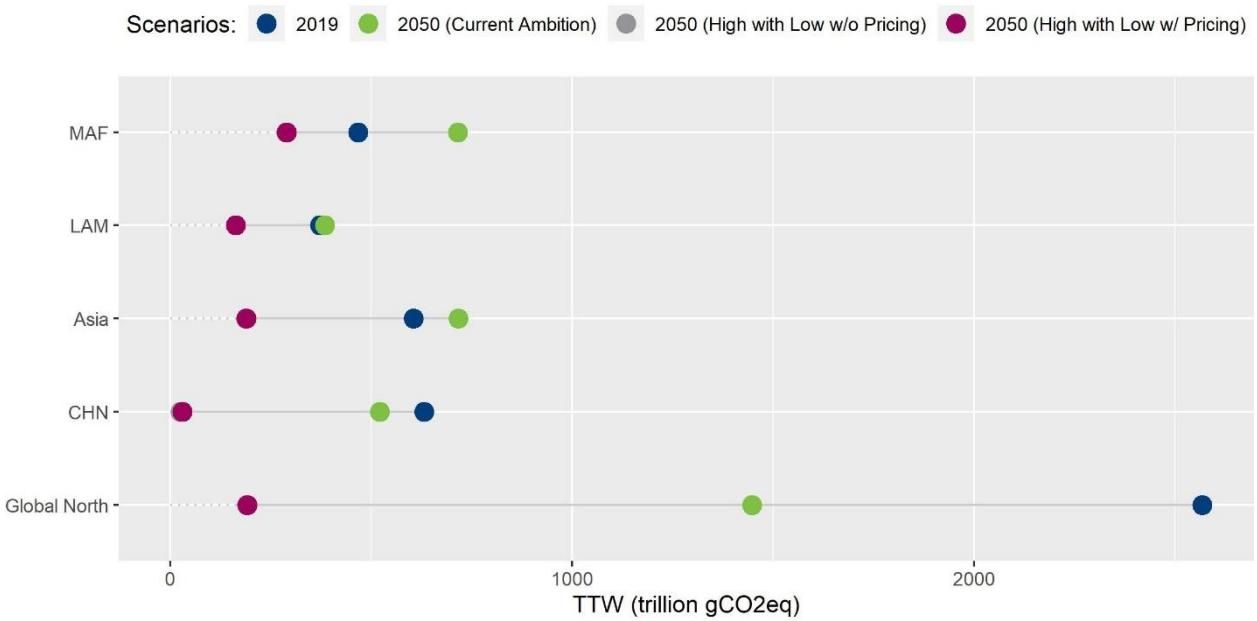
Figure 9: Evolution of passenger-kilometres, energy and tailpipe emissions by region per scenario.



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Figure 10: Comparison of passenger-kilometres and tailpipe emissions by region and scenario

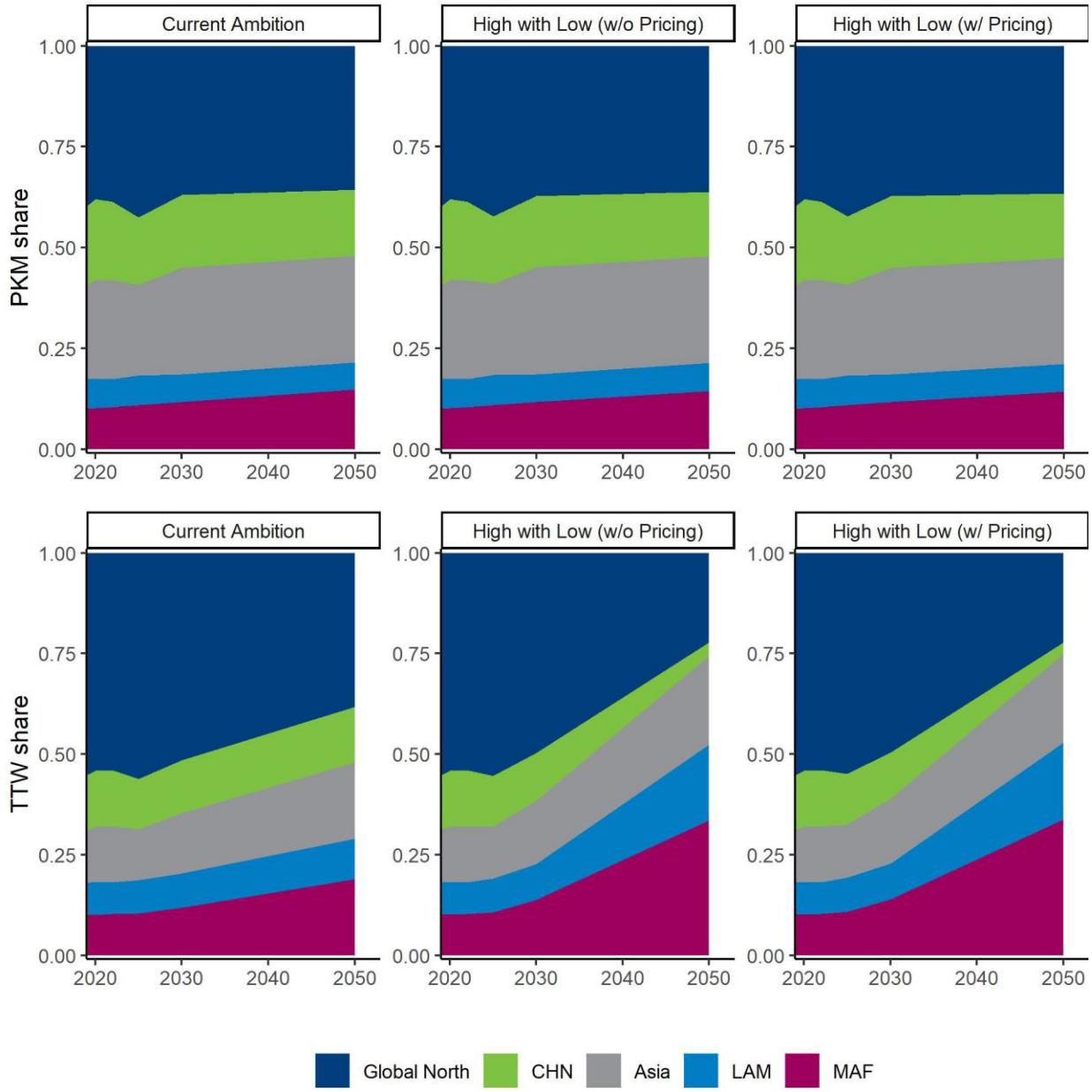




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Global passenger travel activity (pkm) and emissions are not evenly distributed across regions. The Global North together with China in 2019 account for 59% of global pkm and 69% of global CO_2 tailpipe emissions (Figure 11) while they represent 37% of the global population. The projections for the distribution of travel activity among the world regions remain stable between the different scenarios evaluated showing the reduced sensitivity of passenger travel demand to the policy measures implemented within the 'High-with-Low' scenarios. Contrarily, in 2019 the Global North together with China account for more than 69% of the CO_2 emissions and forecasts indicate this share by 2050 to reduce to 52% under the Current Ambition scenario, and to 26% under the 'High-with-Low with Pricing' scenario. Higher level of ambition with respect to technology development (fleet and fuels) reduces the contribution of the Global North to the total global emissions.

Figure 11: Evolution of the share of passenger-kilometres and tailpipe emissions by region and scenario



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References

Benezech, V., L. M. Martinez and J. Kauppila (2016), *Assessing the Long-Term Impact of Air Liberalization on International Air Passenger Demand: A New Model up to 2050*, .

CIESIN - Columbia University (2018), "Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11", NASA Socioeconomic Data and Applications Center (SEDAC).

Grauberger, W. and A. Kimms (2016), "Airline revenue management games with simultaneous price and quantity competition", *Computers and Operations Research*, Vol. 75, https://doi.org/10.1016/j.cor.2016.05.008.

Grubler, A., G. Nemet, S. Pachauri and C. Wilson (2022), *The "High-with-Low" Scenario Narrative: Key Themes, Cross-Cutting Linkages, and Implications for Modelling EDITS WG3 Narratives group* (No. Draft May 27, 2022), .

Hansen, M. (1990), "Airline competition in a hub-dominated environment: An application of noncooperative game theory", *Transportation Research Part B*, , https://doi.org/10.1016/0191-2615(90)90030-3.

IATA (2019), "Airport and location codes", IATA, https://www.iata.org/en/publications/directories/code-search/ (accessed January 15, 2020).

IEA (2019), "IEA Mobility Model", IEA, www.iea.org/topics/transport/mobilitymodelpartnership/ (accessed January 15, 2020).

ITF (2021), *ITF Transport Outlook 2021* (ITF Transport Outlook), OECD, Paris, https://doi.org/10.1787/16826A30-EN.

ITF (2020), *The ITF urban passenger transport model - Insights and example outputs*, International Transport Forum.

ITF (2019), *ITF Transport Outlook 2019*, OECD, https://doi.org/10.1787/transp_outlook-en-2019-en.

Kummu, M., M. Taka and J. H. A. Guillaume (2018), "Gridded global datasets for Gross Domestic Product and Human Development Index over 1990-2015", *Scientific Data*, Vol. 5, https://doi.org/10.1038/sdata.2018.4.

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 (2022), *OECD Economic Outlook*, OECD Publishing, Paris, https://doi.org/http://dx.doi.org/10.1787/eco_outlook-v2016-1-en.

OECD (2020), *Cities in the world: A New Perspective on Urbanisation*, *OECD Urban Studies/European Union*, .

UN DESA (2022), *World Population Prospects 2022*, United Nations.

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The ITF freight transport model: Part of the ITF PASTA framework

- Model framework, insights and outputs for the EDITS 'High-with-Low' Scenario

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The International Transport Forum

The International Transport Forum is an intergovernmental organisation with 64 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.

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Disclaimer

This paper provides insights into the ITF modelling framework that allows for projections of transport demand and its impacts up to 2050. Any findings, interpretations and conclusions expressed herein are those of the authors and do not necessarily reflect the views of the International Transport Forum or the OECD. Neither the OECD, ITF, nor the authors guarantee the accuracy of any data or other information contained in this publication and accept no responsibility whatsoever for any consequence of their use. This work is published under the responsibility of the Secretary-General of the ITF. This document, as well as any data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

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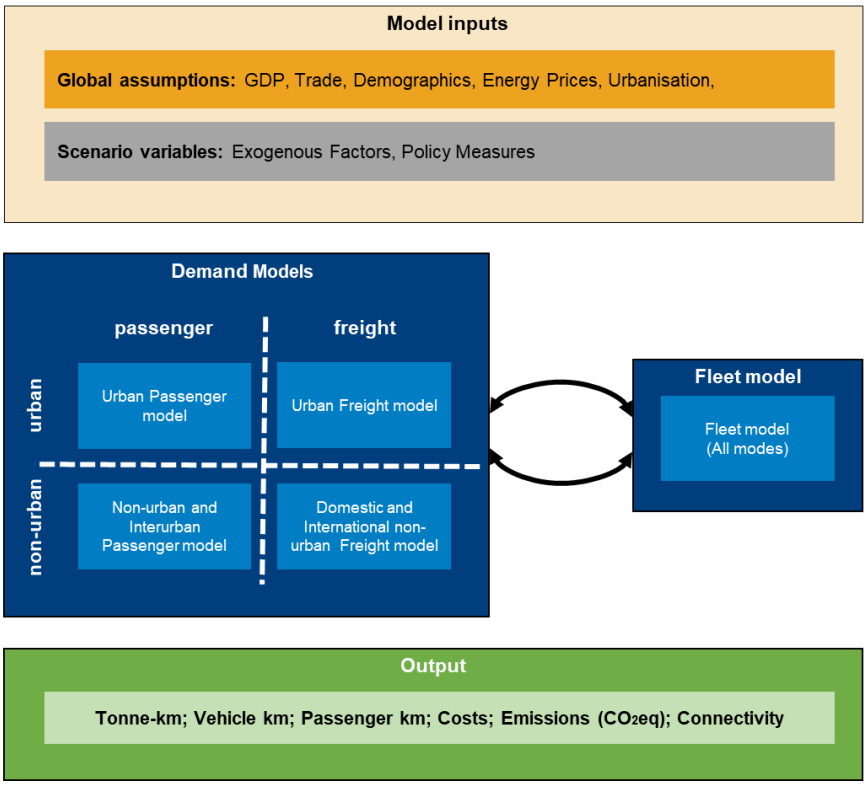
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The ITF PASTA framework and the 'High-with-Low' Scenario

This report describes the ITF freight model inputs, outputs, and components. It also presents results under the EDITS 'High-with-Low' scenario. This global scenario assesses the potential to deliver high wellbeing with low resource consumption.

This freight model is one of the five models that make up the ITF Policy Ambitions and Sustainable Transport Assessment (PASTA) framework. The PASTA framework includes a non-urban (international) freight model, an urban freight model, a non-urban passenger model, and an urban passenger model. It also includes a fleet model that links to the technology development sector and allows for assessing the associated emissions of the transport activity estimated in the other four models.

Figure 1. Simplified ITF PASTA framework



Source: ITF

The report is part of a series describing ITF's transport models covering the global freight and passenger sectors.

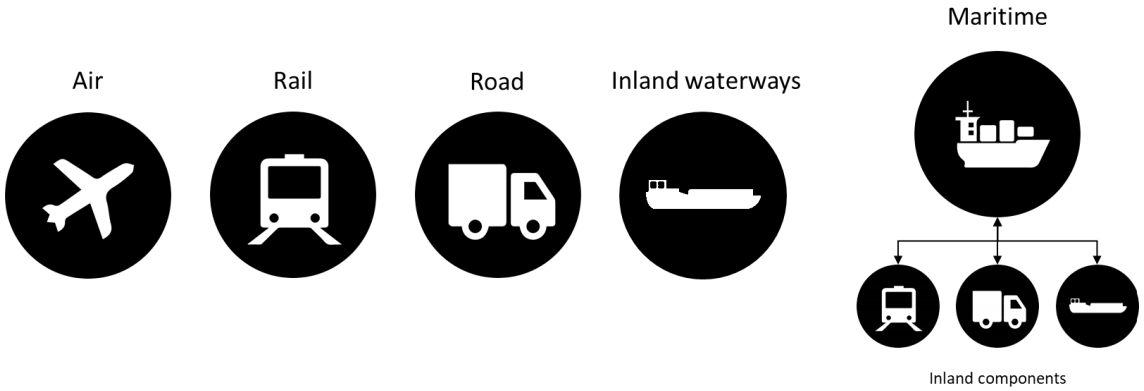
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ITF Freight Model overview

The ITF has developed and updated its freight model to estimate the impact of policy measures on freight transport under different scenarios. The first versions of the model are described in Martinez et al. (2015), ITF (2016), and ITF (2020).

The ITF freight model assesses and provides scenario forecasts for freight flows around the globe. It is a fully integrated multi-modal network model that assigns freight flows on all major transport modes (air, inland waterways, maritime, rail, road) to specific routes, modes, and network links. The maritime freight includes the access and egress inland components, and the mode choice includes rail, road or inland waterway components. Centroids, connected by network links, represent zones (countries or their administrative units) where goods are consumed or produced.

Figure 2. Transport modes distinguished by the model



Source: ITF

The model was developed to estimate the impact of transport and economic policy measures (e.g., the development of new infrastructure networks, the alleviation of trade barriers), technological breakthroughs or improvements (e.g., high capacity vehicles, energy transition of long-distance road freight) and environmental measures (e.g., CO_2 mitigation measures).

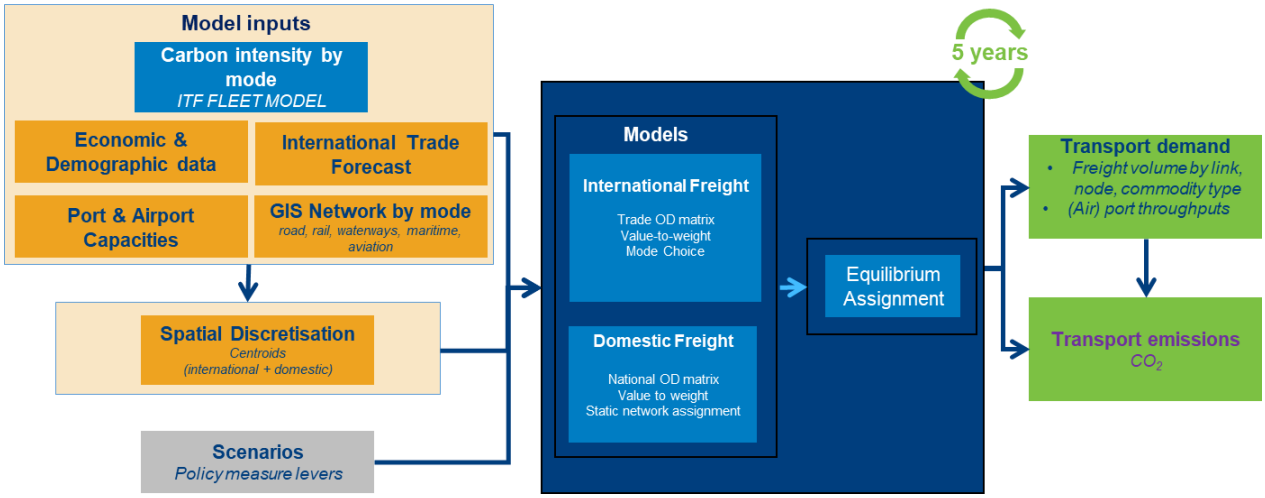
The most recent version of the ITF freight model integrates the (previously distinct) surface and international freight models. International and domestic freight flows are calibrated on data on national freight transport activity (in tonnes-kilometres, tkm) as reported by ITF member countries. Said data is also used to validate the route assignment of freight flows. Trade projections in value terms stem from the OECD ENV-Linkages trade model (OECD, 2021) and are 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 20 commodities for all major transport modes, including sea, road, rail, air and inland waterways. The underlying network contains 8 467 centroids, where goods' consumption and production occur. Of these, 1 164 represent the origins and destinations (ODs) for international trade flows, and 7303 represent the ODs of domestic flows. Each of the 152 863 links of the network is described by several attributes. These include length, capacity, travel time (incl. border crossing times), and travel costs (per tkm).

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The model framework can be found in Figure 3. Each of the components will be described in more detail in the following sections.

Figure 3: ITF Freight model framework



Source: ITF

Model inputs

The model requires inputs of four main categories: trade forecast data; network data for different modes; economic, demographic and geographical data; and initial carbon intensity data by mode (Figure 3).

Trade forecast data originate from the OECD's ENV-Linkages Computable General Equilibrium (CGE) model. This global economic model describes how economic activities are interlinked across several macroeconomic sectors and regions. The model is built primarily on a database of national economies. An economic input-output table underpins each region, usually obtained from national statistics agencies. World trade in the ENV-Linkages model is based on a set of regional, bilateral flows. All flows are expressed in monetary terms, in constant USD, using purchasing power parities as exchange rates for national currencies. The model projects international trade flows in values for 26 regions and 20 commodities up to 2060 (J. Chateau et al., 2014).

Network data is mainly based on open GIS data for different transport modes. The ITF has consolidated and integrated various modal networks into a single routable freight network. For this purpose, networks of the different modes were interconnected by introducing transport links between centroids and using data on intermodal dwelling times. Each link in the network has several characteristics, including its length, capacity, maximum speed, cost, travel times, and border crossing time (where applicable). The costs were estimated based on the network data taking into account distance- and time-based components.

Economic and demographic data include population UN-DESA (2022) and GDP data for regions (OECD, 2022) associated with each centroid. The economic characteristics of each region also include data on the contribution of the main sectors of the economy to the GDP. The main sources for detailed regional accounts are the World Bank open-data database (https://data.worldbank.org/) for single region countries, Eurostat for European countries (https://ec.europa.eu/eurostat/web/national-accounts/regional-accounts) and national accounts for other world countries over 100 million inhabitants.

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Finally, data on the emissions intensity of each mode, as well as their projected changes due to technological and logistical developments over time, come from the in-house fleet model.

Model outputs

The model provides ton-kilometres (tkm) and vehicle-kilometres (vkm) for each link and node in the freight network, disaggregated by transport mode and by commodity type. As such, values can be generated for each OD pair and for single or multi-modal routes. These, in turn, can be aggregated at different geographical scales to provide information on the following:

- Freight volumes leaving or arriving at a centroid, country, region or total and the breakdown of their destinations/origins
- The modal split of the activity by country, region, or total
- Throughput for each port, airport, or border crossing

These results can be further expanded and enhanced in combination with the ITF fleet model. The demand results above are combined with information on related CO_2 intensities and technology pathways by mode to estimate transport emissions to 2050. In the case of road and rail, these coefficients and pathways vary by region, while maritime and air values are considered uniform around the globe.

They key outputs from the combination of the freight and fleet model are then

- Transport CO_2 emissions by mode, country, and region.
- Activity and Emissions by vehicle type and distance bin. I.e., the vehicle types used for trips of different distances

These last outputs are particularly relevant as it allows us to test the viability and feasibility of new and upcoming technologies and formulate policy recommendations to increase the potential benefits.

Model components

The model estimates freight activity separately at domestic and international levels, converging at the end for the shared use of surface transport infrastructure in countries. It has five main components:

1. Spatial discretisation model
2. International freight model
3. Domestic freight model
4. Equilibrium assignment module
5. Outputs module

Once all the components are set, the model is computed sequentially, as presented in Figure 3.

The model is updated in 5-year intervals and makes scenario forecasts up to 2050, with an adapted running template for the years 2019, 2020 and 2022 to reproduce the effect of COVID on freight demand accurately. Consequently, potential future changes to the underlying freight transport network must be accounted for. These may take the form of updates to infrastructure availability, the capacity or speed on certain transport links, or transport costs that may evolve over time, given technological changes. Such potential updates are included in the model via scenarios variables that are updated in line with a 'calendar of development' of the scenario. The model user can easily change those input parameters. For example,

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in the case of Europe, a detailed calendar representing the TEN-T network[1] development, accounting for its attributes, has been implemented. Information on European intermodal terminals, including their expected delay times, has also been incorporated[2].

[1] Detailed information available at: <https://ec.europa.eu/transport/themes/infrastructure/ten-t_en>.

[2] Detailed information available at : < http://www.intermodal-terminals.eu/database >.

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Detailed model component descriptions

Spatial discretisation model (centroids)

This sub-model defines two sets of centroids: international freight centroids and domestic freight centroids.

International freight centroids

International freight centroids are used to discretise regional OD trade flows into larger production/consumption centroids. The discretisation allows for a proper breakdown of the travel path used for different types of products and leads to a better representation of actual freight flows.

An adapted *set coverage* algorithm was implemented to identify centroids based on a larger set of potential centroids. These potential centroids are all global cities with a population of fewer than 300 000 people, as identified by the United Nations in 2010 (2 539 cities) (UN, 2015). The objective function minimises the number of centroids under the constraints that only one centroid can exist within a 500km radius (in the same country), while the total of the globe's land surface has to be attributed to a centroid.

Figure 4. International freight centroids



Source: ITF

This algorithm was adapted for some regions where increased spatial detail was desired in view of potential future studies to be carried out by the ITF. For the European Union, the adopted resolution level was the NUTS3 level in regions where a Functional Urban Area (FUA) is present and NUTS2 for the others (i.e., each of the NUTS3 or NUTS2 regions (where applicable) is represented by one centroid).

1 164 centroids were defined. Each centroid is named after the most representative city in the region that the centroid represents.

The influence area of each centroid is computed based on a raster world surface map. Each raster cell is assigned to a centroid based on its distance to the centroid, while cells within a country will always be assigned to a centroid within that same country. Each centroid is characterised by population and GDP

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indicators. Raster cells were linked to global population estimates (CIESIN - Columbia University, 2018) and raster-based information on GDP (Kummu et al., 2018) are used to estimate the population and GDP.

Domestic freight centroids

Domestic freight centroids define the origins and destinations of domestic freight flows. These centroids are estimated by a *set coverage* algorithm similar to the one described above. It uses raster-based GDP data (Kummu et al., 2018) to identify the most representative raster cell within a 100km radius.

The model produces a total of 7303 domestic centroids distributed as follows: North Africa (22), Central Africa (1020), South Africa (482), Commonwealth of Independent States (CIS) + Mongolia (823), South America (968), Central America and Caribbean (262), North America (845), ASEAN member countries (509), China (553), India (248), Japan and Korea (69), Oceania (249), Middle East (450), other Asian countries (70), European Union (452) and Other European countries and Turkey (145)).

As is the case with international freight centroids, the influence area of each domestic freight centroid is computed based on a raster world surface map. Population and GDP estimates are linked to each centroid while again respecting country boundaries (each raster cell is assigned to a centroid that lies in the same country as the raster cell, based on its distance to the centroid). Figure 3 provides an overview of the domestic freight centroids that have been defined in ITF's freight model.

Figure 5. Domestic freight centroids



Source: ITF

International freight model

This model includes a global intermodal network sub-model, underlying international trade projections, a weight-value conversion sub-model, and a mode share sub-model

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Intermodal global network model

One of the main contributions of ITF's freight model is the consolidation and integration of different modal networks into a single freight network. Box 1 provides an overview of the data sources that were used to establish the respective transport network information in the model.

Box 1. Sources of information for global transport networks

- **Road network** information stems from the Global Roads Open Access Data Set (gROADS) (http://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1) and OpenStreetMap (www.openstreetmap.org). Only the first and second road networks are considered (i.e. motorways, main roads and truck roads).
- For the **rail network**, the model uses data from the Digital Chart of the World (DCW) (http://www.princeton.edu/~geolib/gis/dcw.html) project that is updated with data from OpenStreetMap on rail lines and rail stations as intermodal points of connection between road and rail.
- **Maritime routes** are obtained from the Global Shipping Lane Network data of Oak Ridge National Labs CTA Transportation Network Group (http://www-cta.ornl.gov/transnet/Intermodal_Network.html), which generates a routable network with actual travel times for different sea segments. This network is connected to ports based on data from the latest World Port Index Database of the National Geospatial-Intelligence Agency (http://msi.nga.mil/NGAPortal/MSI.portal).
- Commercial **air links** between international airports were integrated using data from the OpenFlights.org database on airports, commercial airlinks and airline companies (www.OpenFlights.org).
- **Inland waterways** around the world were collected from the DIVA-GIS project (https://www.diva-gis.org). Their navigability was assessed by specific information about the rivers and the sections that are navigable.
- Information on **oil or gas pipelines** was also obtained from OpenStreetMap (www.openstreetmap.org).

All the above transport networks were interconnected with road-based transport links (*connectors*) that connect the centroids to the network but also interconnect the different transport infrastructure (e.g. road-rail, road/rail-ports, etc.). In order to estimate travel times for the different types of transport infrastructure, as well as dwelling times between transport modes, the model uses average speeds based on available information by region. Border crossing times were estimated based on available datasets from TAD/OECD (http://www.oecd.org/trade/topics/trade-facilitation/).

The data sources provided in Box 1 were also used to establish transport costs for the different links. These costs encompass a distance-based and a time-based cost component. The distance-based cost component for each type of infrastructure is matched to a different unit value per region or country that takes into account infrastructure quality/performance, fuel/energy costs and labour costs in the transport sector.

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The methodology for these calculations was derived from Tavasszy et al. (Tavasszy et al., 2011), where the authors establish a procedure to estimate indicators for the total costs for a link/network. The values obtained for specific countries were calibrated so to match reported mode shares by these countries. The time-based cost component reflects the value of travel time. An average aggregate value of time per hour and ton of 0.196 dollars/h.ton is derived from Tavasszy et al., 2011. Commodity-specific values of time are estimated in the mode choice model, where a distinct time-sensitiveness is obtained for each commodity type and transport type (container-based cargo, dry bulk, liquid bulk, transport equipment – RoRo and general cargo - more details are provided in Table 2).

The network model computes the free flow shortest paths between all centroids for each transport mode (if the mode is available), generating inputs used in the main econometric models (weight-value model and mode share model) presented next. These inputs are:

- The cost, travel time and distance by mode to link each pair of centroids;
- The shortest paths between the centroids for each transport mode.

Underlying international trade projections

The underlying trade projections that are used as an input to the model are disaggregated into 26 world regions. This level of resolution does not allow for estimating transport flows with precision as it does not allow a proper discretisation of the travel paths of different types of products. Therefore, the model disaggregates the regional origin–destination (OD) trade flows into the set of production/consumption centroids as defined in the spatial discretisation model. The disaggregation procedure assumes a proportionality of trade to GDP and uses raster-based GDP and population information to disaggregate trade estimates at the regional level. It matches this information for the base year (2019) if the information is available in the UN Comtrade (2022) dataset.The GDP used in the disaggregation of each commodity just considers the GDP created within the respective economic sector. This is determined as a national or regional share (depending on data availability) of each economic sector multiplied by the estimated raster-based GDP. In the GDP of the EU, the NUTS3 or NUTS2 disaggregation was used to estimate this share.

Growth projections of centroids are based on the growth rates at the country level obtained from the OECD 2013 Economic Projections (Jean Chateau et al., 2014), as growth rates are available at a country level only. The split of trade activity of centroids within the same country as source/destination of trade is kept constant over time.

The resulting equation for the estimation of the trade flows between centroids (OD pairs) for each type of commodity is given by

$$T_{odk}^{y} = T_{VLk}^{y} \frac{GDP_{o}^{y} \cdot S_{of(k)}}{\sum_{v=1}^{V} GDP_{v}^{y} \cdot S_{vf(k)}} \frac{GDP_{d}^{y}}{\sum_{l=1}^{L} GDP_{l}^{y}} \quad (1)$$

Where
T_{odk}^{y} = trade values from centroid *o* to centroid *d* in year *y* for commodity *k*,
T_{VLk}^{y} = trade values from origin region *V* to destination region *L* in year *y*,
$S_{of(k)}$ = share of GDP related with the same economic sector of commodity *k* in the region or country of centroid *o*,
o, *d* = origin and destination centroids,
k = commodity *k*,
y = year of analysis,
k = centroid that belongs to the origin region *V*,
l = centroid that belongs to the destination region *L*.

Weight-value model for the international trade

The conversion of value units (dollars) into weight units (tons) of cargo was formulated as a Poisson regression model. The model estimates the rate of value-to-weight conversion, using as offset variable the natural logarithm of the trade value in million dollars and a panel term representing the sensitivity of the different commodity types to transport costs. The selection of this regression method was based on the observation of the statistical distribution of the sample that fitted better a discrete statistical distribution than continuous distributions, especially for low trade connections. The model equation is given by:

$$E(y) = F \cdot exp(a + X\beta) + \varepsilon \quad (2)$$

where F is the exposition factor and X represents the systematic component of the Poisson regression model.

The model was calibrated using Eurostat and ECLAC exports data[3] provided in value and weight units and using transport cost information (stemming from the network model, as discussed above). Also, geographical and cultural variables were used to estimate the model parameters: binary variables for trade agreements, land borders and for reflecting whether two countries use the same official language were introduced. Moreover, economic profile variables were included to describe the trade relationship between countries and the scale of trade intensity. These are

- The GDP percentile of the origin country ($p\%\ GDP_i$);
- The GDP percentile of the destination country ($p\%\ GDP_j$);
- The GDP per capita percentile of the origin country ($p\%\ GDP\ capita_i$);
- The GDP per capita percentile of the destination country ($p\%\ GDP\ capita_j$);
- The natural logarithm of the GDP per capita ratio between origin and destination countries ($ln\frac{GDP\ capita_i}{GDP\ capita_j}$).

All the economic variables were defined using a relative order of countries in terms of percentiles instead of their absolute values. This is to avoid any disproportional effect in the future relation of value to weight. Any changes here are not expected to happen as it is neither assumed that products will become lighter for the majority of the commodities, especially with regards to raw materials, nor that a disruption in the market will significantly change the valuation of some commodities over others.

As a result, the values estimated by the model assume a stability of both the commodities' valuation over time and of how productivity indicators may impact them. Yet, the value-weight conversion of some energy market-related products, such as crude oil, refined oil, gas and coal, will depend strongly on the price of these commodities over time. For this reason, the value-weight conversion of these commodities has been indexed to the value forecast by IEA/OECD (IEA, 2018b) to ensure consistency in terms of the forecasted volume of trade for the next decades.

The model was estimated by keeping the minimum effect of the cost log sum positive and all commodities sensitive to costs. The minimum threshold value of 0.025 was estimated for the panel terms based on the observations in the dataset. The log sum accounts for the generalised costs, incorporating the time-based and distance-based cost terms.

[3] https://sgo-win12-we-e1.cepal.org/dcii/sigci/sigci.html

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Table 1 presents the calibration results for the model.

Table 1. Weight-value model calibration results

Parameter	Coefficient	p-value/ level of significance
Intercept	-13.907	0.00
Economic profile of countries		
$p\%\ GDP_i$	0.123	0.02
$p\%\ GDP_j$	-0.074	0.11
$p\%\ GDP\ capita_i$	-2.22	0.00
$p\%\ GDP\ capita_j$	1.08	0.00
$lnGDP\ capita_i GDP\ capita_j$	0.686	0.00
Economic, geographical and cultural relations between countries		
$Land\ border_{ij}$	-0.406	0.00
$Same\ language_{ij}$	0.133	0.01
$Trade\ aggreement_{ij}$	0.114	0.03
Cost commodity panel term $logsum\ cost\ dollartonne$		
Chemicals	- 0.136	0.12
Coal	- 1.679	0.00
Crude oil	- 0.395	0.00
Electronics	- 1.161	0.00
Fishing	- 0.392	0.01
Food products	- 1.324	0.00
Forestry	- 0.244	0.01
Gas	- 2.573	0.00
Iron and Steel	- 2.335	0.00
Livestock	- 0.277	0.01
Metal products	- 1.187	0.00
Non-Ferrous Metals	- 0.025	-
Non-metallic minerals	- 1.233	0.00
Other manufacturing	- 0.025	-
Other mining	- 0.025	-
Paper, pulp and print	- 0.245	0.00
Petroleum & coke	- 1.147	0.00
Rice and crops	- 0.524	0.00
Textiles	- 0.195	0.06
Transport equipment	0.025	-
(Scale)	1	
Pseudo-ρ^2	0.73	
Correl (y, y)^2	0.92	

Source: ITF

The overall model fit is high and shows the ability of the model to predict the conversion of trade values into trade volumes (in tons). The model performs well in reproducing market patterns. The trade agreement variable reveals to be a relevant explanatory factor; more expensive goods are typically transported further away. All the economic variables were found to be significant, presenting interesting relations for the weight-value ratio. Coefficients for $p\%\ GDP_i$ and $p\%\ GDP\ capita_j$ have a positive sign, indicating that larger economies tend to export larger weights/values, and wealthier destination countries tend to import larger quantities. There is quite symmetrical behaviour in terms of the size of destination markets and their wealth, showing that for less developed countries, it is more expensive to access

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products in the market. When there is a large difference in wealth between countries, the model predicts the import of higher-value goods to the wealthier country.

The cultural relation between countries (set as a binary value that takes the value one if the origin and destination country have a common official language and/or had a colonial relation in the past) was also found to be significant. Such country relations lead to relatively more exports of greater-value products. Conversely, countries with a land border tend to export larger quantities due to lower export costs.

Regarding the sensitivity of commodity types to transport costs, it can be seen that bulk-type commodities (liquid or solid) tend to be quite sensitive to costs. For example, textiles and other manufacturing products are less sensitive to transport costs. The value obtained for electronic components is also quite high, showing that trade volumes for electronic products are pretty sensitive to transport costs.

Mode share model for international freight

The mode share model for international freight flows (in tonnes) defines the transport mode used for trade between any OD pair of centroids. The modes include air, rail, road, waterways and maritime transport. The overall mode attributed to each trade connection represents the longest transport leg in a multi-modal trip chain. All freight is typically shipped on multi-modal chains, especially as the first and last legs are usually different from the main mode of transport. These latter domestic components of international freight movements are often unaccounted for in the literature. The ITF model does integrate these components: In the case of maritime transport, the model distinguishes one of three access modes (rail, road or waterways, while for the other non-road modes, the access mode is always assumed to be road.

The model uses a nested multinomial logit formulation, including a time commodity type panel term and a type of freight cost panel term. The mathematic formulation is given by:

$$U_{nj} = X'_{nj}\beta + Z'_s\alpha + \varepsilon_{nj} \quad (3)$$

where Z'_s represents characteristics of the nests, and ε follows a generalised extreme value (GEV). ε_{nj} have a joint cumulative distribution function of error terms, which is defined by

$$F(\varepsilon_{n1}, \varepsilon_{n2}, \dots, \varepsilon_{nJ}) = exp\left(-\sum_{s=1}^{S}\left(\sum_{j\epsilon B_s} e^{-\varepsilon_{nj/\lambda_s}}\right)^{\lambda_s}\right) \quad (4)$$

Where $\lambda_s$represent the nesting parameter that characterises each nest belonging to S.

The model was calibrated using export data sets from Eurostat and ECLAC, which contain information on the value, weight and mode of transport for exports from the EU and Latin America to the rest of the world. For each OD pair, we estimate the modal share in weight by commodity group. Data on travel times and distances for each mode were taken from the global network model at the centroid level. Two geographical and economic context binary variables were added: one describing if the pair of countries have a trade agreement and the other for the existence of a land border. For every OD pair, available modes were identified (e.g. land connectivity). Some commodity classes, such as coal and crude oil, cannot be shipped by air.

The dataset contained 17 427 observations, with an average weighted mode share in weight units of 19% for road, 1% for air, 79% for sea and just 1% for rail. The calibrated model has the likelihood ratio index (pseudo-rho squared) ρ^2= 0.64, showing very strong explanatory power of the mode choice. All explanatory variables are statistically significant (see Table 2).

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Table 2. Trade value international freight mode share calibration results

Variable	Coefficient	Robust t-test	Robust p-value
Mode specific constant			
Air	-2.921	-41.50	0.00
Rail	-2.024	-40.22	0.00
Road	0.150	12.42	0.00
Lambda (nest parameter)	0.754	2.56	0.00
Sea – access by road	0.963	1.87	0.01
Sea – access by rail	0.550	2.01	0.00
Sea – access by waterways	1.050	1.65	0.02
Waterways	-0.801	1.52	0.04
Time commodity panel (1 000 hours)			
Chemicals	-0.191	-6.14	0.00
Coal	-0.002	-15.21	0.00
Crude oil	-0.153	-25.64	0.00
Electronics	-0.383	-157.44	0.00
Fishing	-0.097	-99.28	0.00
Food	-0.305	-33.33	0.00
Forestry	-0.010	-32.89	0.00
Iron and Steel	-0.014	-30.19	0.00
Livestock	-0.096	-2.65	0.00
Metal products	-0.393	-32.11	0.00
Non-ferrous metals	-0.112	-23.14	0.00
Non-metallic minerals	-0.006	-52.56	0.00
Other manufacturing	-0.177	-40.15	0.00
Other mining	0.000	0.00	-
Paper, pulp and print	-0.045	-39.6	0.00
Petroleum & coke	-0.003	-15.14	0.00
Rice and crops	-0.008	-22.11	0.00
Textiles	-0.008	-2.81	0.00
Transport equipment	-0.102	-35.18	0.00
Cost type panel term (1 million dollars)			
Container-based	0.03	-4.78	0.00
Dry bulk	0.06	-10.24	0.00
General cargo	0.02	-5.38	0.00
Liquid bulk	-0.07	-13.25	0.00
Transport equipment (Ro-Ro)	-0.02	-6.51	0.05
Geopolitical variables (trade agreement effects – TA, land border – LB)			
TA (rail and road)	1.33	4.47	0.00
LB rail	0.978	28.11	0.00
LB road	1.33	92.99	0.00

The results show a greater relationship between the sea alternative and low-value raw materials and non-perishable products. Transport-related variables present an interesting behaviour that clearly distinguishes sea transportation from the other available options. While increases in travel time reduce the utility of transporting by sea, cost aspects ensure the attractiveness of this mode. In general, the utility of a sea trade connection will depend on the balance between cost and travel time, often defined by specific sea routes and/or possible connections. Sea routes requiring a significant detour from the direct link are less attractive. Sea routes from Europe to Asia that do not use the Suez Canal are an example of such less attractive routes.

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Air cargo has a very negative independent term due to the inability to send large volumes or because there are security concerns for specific commodities (chemicals, rubber and plastic, refined oil, livestock, other metals, other minerals, coal, iron and steel, crude oil, other mining, rice and crops and gas). The absence of direct flights is also very penalising (increasing the travel time and reducing utility significantly). Road and rail present similar utility behaviours. Yet, the alternative specific constant for rail is quite negative. This indicates that (although the cost for this mode is significantly lower than the one for road) its attractiveness is relatively low due to operational requirements that entail large delays and reliability concerns. This is partly due to the large number of rail operators involved in cross-national rail shipping.

Other important elements are geopolitical variables:

- Trade agreements between countries seem to favour land-based transport, indicating a potential simplification of border crossings procedures;
- A land border between countries favours exports through road and rail. Yet, this is stronger for road as the potential rail interoperability issues are still present.

Domestic freight model

Inversely to a traditional four steps model, the modelling of domestic freight does not follow the generation, distribution and assignment sequence. As no trade estimates between the different regions and cities of any one region are available, the model departs from the total freight activity estimation and follows a gravitational model to understand how the total trade splits into an OD matrix between the domestic freight centroids.

For each country, the gravitational impedance and the distance for each available mode among the domestic freight centroids allow the estimation of an average domestic travel distance. The total domestic freight activity (in tkm) is then divided by the average distance to obtain the average freight cargo weight. This weight can then be assigned to the network following the OD matrices and the shortest path between domestic centroids for the different available modes.

The two main steps of this model are presented next.

Estimates of total surface freight activity

Total surface freight activity in ton-kilometres is estimated by country. This includes all movements by road, rail and inland waterways inside each country's borders, encompassing transport of international and domestic nature, plus urban freight transport.

A Poisson regression model was used and calibrated on sample data from 51 countries from 2010 to 2015 with 306 observations. Observations cover all major countries that correspond to more than 80% of the world's surface freight movements (in ton-kilometre). Data assessments and extensive tests showed that using a discrete statistical distribution is more suitable than using a continuous distribution (e.g. lognormal) given the wide range of values and country behaviours. The natural logarithm of industrial- and agriculture-related GDP shows a higher correlation with freight activity than GDP *per se*. Therefore, it was used as an offset (or exposition factor) in the function. More than any other factor, this guides the trend and determines the volume of transport in each country. Other variables are related to the countries' geography, transport networks, and socio-demographic and economic structure (Table 3). The resulting equation is given by:

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$$E(y) = F \cdot exp(a + X\beta) + \varepsilon \quad (5)$$

where F is the exposition factor and X represents the systematic component of the Poisson regression model.

Model calibration results show the number of factors that favour surface freight transport volumes. These include a country's size, the existence of large ports, the facts of being landlocked or having natural resources rents and ore-metal exports as a relevant part of the GDP (>12%). Also, having a geographical location and transport infrastructure that allows for transit plays an important role. Conversely, very high GDP per capita and population densities tend to reduce activity, meaning that richer economies are less transport intensive. Likewise, countries with higher densities show less freight transport activity, as there are only shorter distances to cover.

Table 3. Total surface freight activity calibration results

Parameter	Coefficient	z - value	Significance
Intercept	-14.890	-22723.6	0.00
Country profiles			
Connectivity for transit (1 000 000 km)	1.871	796.3	0.00
Population density (1 000 inhabitants/sqm)	-1.057	-574.9	0.00
Arable land (1 000 000 sqm)	0.516	1323.1	0.00
Dummy variables			
Inland waterways in activity	0.214	522.9	0.00
Large ports (in the 90 percentile of ports by capacity)	0.191	385.4	0.00
Landlocked	0.438	640.5	0.00
Natural resources rents and ore/metal exports	0.249	668.8	0.00
Fast growing (above 5% GDP growth)	0.192	552.5	0.00
Large countries in area (>1 200 000 km^2)	0.702	1283.8	0.00
Very low GDP per capita (< 4000 USD)	0.304	358.3	0.00
Low GDP per capita (4000 – 20 000 USD)	0.364	-493.0	0.00
Very high GDP per capita (> 40 000 USD)	- 0.316	568.8	0.00
(Scale)	1		
Pseudo-ρ^2	0.94		
Adjusted ρ^2	0.99		

Note: Offset (parameter with coefficient 1) for Industrial and Agriculture related GDP. Source: ITF

All variables in the model are significant, and the pseudo-R squared has a high value of 0.94.

Data sources for freight movements include ITF's surface freight database (ITF, 2017a), Eurostat, US DOT, and other national statistical agencies. GDP composition and natural resources intensity of the economy was obtained from the World Bank database. Ports capacity comes from the data set developed for ITF (2016). The *connectivity for transit traffic* is an indicator that measures the route-kilometres that can take place in each country for movements between contiguous countries or countries that share the same trade agreements, the global road network and centroids for international trade where used for this calculation.

Part of the activity estimated by this model is already allocated to the network since it comes from international trade. The global intermodal network does not include urban activity, so the total volumes of urban freight per country are accounted for, including the estimates for emissions, but no mode choice or network allocation is performed. The share of urban versus non-urban freight transport activity in each country is obtained from the IEA's MoMo database (IEA, 2018b) as default. This information is complemented with ITF country survey information for member countries.

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The activity that does not correspond to urban or international trade-related movements is subjected to mode-route choice using an *all-or-nothing* assignment procedure (see next section).

Mode route choice for domestic freight

Domestic freight activity (in tkm) is estimated in alignment with international freight activity estimates and domestic freight weights (in t).

The shortest paths between all centroids within the same countries are computed for all existent surface modes (road, rail and waterways) considering their attributes (e.g. cost and travel time). A simple gravity with the following formulation is applied:

$$V_{ij} = p_i * P_i * q_j * C_j * f(c_{ij}) \quad (6)$$

In this equation, V_{ij} denotes the transported freight from zone i to zone j, while P_i and C_j are the reported production and consumption of freight in the corresponding zones multiplied by zone-specific multiplication factors s p_i and q_j.These are multiplied by function f that determines the accessibility of the destination zone based on the generalised cost between zones c_{ij}:

$$f(c_{ij}) = e^{-\beta c_{ij}} \quad (7)$$

In this function, β is a sensitivity parameter that is estimated to be 0.00045, while c_{ij} defines the impedance between centroids (i.e. the zones that they represent), taking into account travel times and costs. The model generates a distribution of origin-destination flows by mode within the same country. The resulting matrix allows estimating the average travel distance of a freight movement and converting the tkm into weight. These flows (in weight terms) are assigned to the intermodal transport network model and are there subject to potential congestion also stemming from international traffic.

Equilibrium assignment

The model uses an iterative equilibrium assignment procedure with travel time and cost updates at every iteration (5 years). This also accounts for transport infrastructure updates in line with the 'calendar of development' that provides information on how infrastructure develops over time (e.g. accounting for TEN-T networks for Europe) - in terms of availability and/or link attributes (speed and capacity). Some components of the network are also assessed in terms of capacity and resulting congestion. Port capacity and throughput are also updated every iteration, using the information on planned port capacity expansions as reported at individual porta- or in the form of regional average growth rates. Port-specific data has been obtained from maritime studies (Drewry, 2013; OCS, 2012c, 2012a, 2012b).

At every iteration, freight transport activity by mode is assigned to the shortest/least-costly path (based on minimising the generalised cost). In the case of maritime shipments, a route choice model also considers the available .alternatives for port selection and transhipment options for every OD pair. The introduction of this procedure in the overall equilibrium assignment reduces the number of iterations required to converge. For creating the routing alternatives between each pair of centroids, a shortest path algorithm is computed between ports to generate the port-to-port segment(s) – consider both direct routing or indirect routing via a transhipment port). Transhipment ports are limited to large ports (more than 1 million TEUs of container traffic capacity, assuming an increase of this threshold value of 3% per year) with more than 25% spare capacity in the previous iteration.

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The route and port choice algorithms use a path size logit model, which accounts for overlaps between alternative routes and transport costs associated with each alternative. The basis of this model can be found in (Bottom et al., 1999). The model is calibrated by minimising the difference between observed and modelled port throughputs for more than 400 major ports in the world. A detailed description of the model can be found in (Halim et al., 2016) and in (Tavasszy et al., 2011). The formal definition of the cost model is

$$\boldsymbol{C_r} = \sum_{\boldsymbol{p}\in\boldsymbol{r}} \boldsymbol{A_p} + \sum_{\boldsymbol{l}\in\boldsymbol{r}} \boldsymbol{c_l} + \boldsymbol{\alpha}\left(\sum_{\boldsymbol{p}\in\boldsymbol{r}} \boldsymbol{T_p} + \sum_{\boldsymbol{l}\in\boldsymbol{r}} \boldsymbol{t_l}\right) \tag{8}$$

where

C_r = unit cost of route r from origin centroid to destination centroid (USD/Twenty-equivalent unit, TEU),

p = ports used by the route,

l = links used by the route,

A_p = unit cost of transhipment at port p (USD/TEU),

c_l = unit cost of transportation over link l (USD/TEU),

T_p = time spent during transhipment at port p (days/TEU),

t_l = time spent during transportation over link l (days/TEU),

α = value of transport time (USD/day).

The following is the formal definition of the route choice model. The route probabilities are given by

$$P_r = \frac{e^{-\mu\,(C_r + \ln S_r)}}{\sum_{h=1}^{H} e^{-\mu\,(C_h + \ln S_h)}} \tag{9}$$

while the path size overlap variable S is defined as

$$S_r = \sum_{a\,\in\,LK_r} \frac{\mathrm{Z}_a}{\mathrm{Z}_r} \frac{1}{\mathrm{N}_{ah}} \tag{10}$$

In Equations (8) and (9):

P_r = the choice probability of route r,

C_r = generalised costs of route r,

C_h = generalised costs of route h within the choice set,

CS = the choice set with multiple routes,

h = path indicator/index,

μ = logit scale parameter,

a = link in route r,

S_r = degree of path overlap,

$\mathrm{Lk_r}$ = set of links in route r,

Z_a = length of link a,

Z_r = length of route r,

N_{ah} = the number of times link a is found in alternative routes.

At every iteration, the equilibrium assignment produces an all-or-nothing assignment (subject to the travel time and costs update at each assignment iteration) of all transport alternatives simultaneously. The model runs until there is a convergence of travel costs of all alternative paths for the same OD pair. The model typically converges after 5 to 10 iterations.

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Calculation of the outputs

The model provides ton-kilometres (tkm) and vehicle-kilometres (vkm) for each link and centroid in the freight network, disaggregated by transport mode and commodity type. This allows calculating the corresponding values for different origin-destination pairs and routes. These outputs can be further aggregated at country and regional levels.

CO_2 emissions are estimated for each commodity either via transport activity in tkm or vkm, depending on the mode. For road transport, CO_2 is estimated via vkm, using specific load factors of trucks for the different types of commodities. Base load factors, specific for each commodity type, were obtained from the USA Commodity Flow Survey 2017[4] and Eurostat (the European Road Freight Transport (ERFT) survey).

Load factors change over time as operational improvements in freight transport are assumed to happen. These will allow reducing empty vehicle kilometres and making better use of vehicle volumes (e.g. by better packaging). For other modes, CO_2 estimates are derived by tkm. Respective CO_2 intensities per tkm were obtained from:

- ITF fleet model (road, rail and waterways)
- IMO (maritime freight) (Smith et al., 2014),
- ICAO (air cargo) (ICAO, 2018).

[4] https://www.census.gov/programs-surveys/cfs.html

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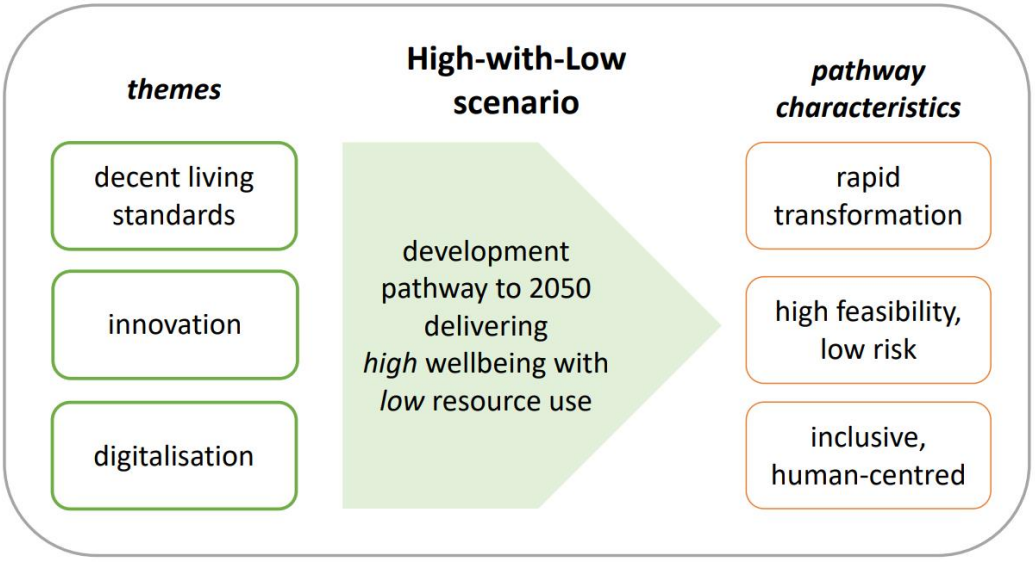
'High-with-Low' scenario information

The ITF models were designed and further updated to estimate and evaluate the impact of policy measures on transport activity and related emissions under the 'High-with-Low' scenarios.

The Baseline scenario builds on existing policies and commitments to estimate the current pathways of transport demand and related emissions. It was built by the ITF in 2020 for the preparation of the ITF Transport Outlook 2021 (ITF, 2021) and updated for the forthcoming ITF Transport Outlook 2023. It is the result of an international survey on current transport policies and technology development implementation all over the world, filled by many experts in the ITF network.

The 'High-with-Low' scenario narrative has been designed by the EDITS research network and described in-depth in Grubler et al. (2022). This 'High-with-Low' scenario aims to achieve high levels of human wellbeing that are more equitably distributed while drastically reducing energy and material consumption. In contrast, the Baseline scenario only represents the current pathways of existing policies and developments. High-with-low relies on three main themes displayed in.

Figure 6 Main themes and characteristics of the development pathways to 2050 of the 'High-with-Low' scenario, from (Grubler et al., 2022).



'High-with-Low' Freight measures and scenario definition

Two variations of the High-with-low scenario are considered. The first scenario meets the High-with-low criteria but does not include additional pricing measures. It represents a 'High-with-Low' scenario where individuals are not financially penalised for reaching climate objectives. The second High-with-low scenario adds pricing policies (e.g., carbon pricing, road pricing, parking pricing).

It should also be noted that these pricing measures are higher for richer countries, namely the Global North and China.

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Table 4 shows the measures implemented in the model. They include enhancement to the infrastructure, economic instruments, regulatory instruments and measures to stimulate innovation and development.

Table 4. List of measures for non-urban freight transport and their implementation in the model

Type	Policy measures	Model	High with Low	
			Global North	Global South
Enhancement of Infrastructure	Electric road infrastructure	Update costs and the resulting CO2 emission per vkm for road. This affects the value-weight conversion and the modal split	30% - 50% of TKM	0% - 15% of TKM
	Consolidation centres and platform sharing	This increases load factors in all modes (more the high capacity), but also, the logistic costs increase. This impacts mode choice and the conversion of tkm to vkm and reduces the conversion of value to weight	20% improvement	10% improvement
	Carbon pricing	Adapt the cost of each mode to reflect the CO_2 cost per km. Impacts mode choice and route choice	500 to 750 dollars per tonne	300 dollars per tonne
Economic instruments	Congestion or distance-based charges	Road costs would update costs based on verified congestion at each road link. Impacts mode choice and route choice	6.2 cents/tonne.km	2.4 cents/tonne.km
	Fuel economy standards – for vehicles and fuel	This element may only impact the CO2 intensity of the affected modes and the conversion of vkm to CO2 emissions	ITF 'High Ambition' scenario	
Regulatory instruments	Operation of shared assets	The adoption of shared assets allows the increase of load factors in road-based modes. This impacts mode choice and the conversion of tkm to vkm	20% improvement	10% improvement
	Low-carbon fuels	This element may only impact the CO_2 intensity of the affected modes and the conversion of vkm to CO_2 emissions	ITF 'High Ambition' scenario	
Stimulation of innovation and development	Platooning	This is implemented by decreasing road costs and load factors of trucks. This impacts mode choice and the conversion of tkm to vkm	5%-20% of TKM	2%-5% of TKM
	Autonomous vehicles	This is implemented by decreasing road costs. This impacts mode choice and the conversion of tkm to vkm	5%-20% of TKM	2%-5% of TKM
	Slow-steaming and Smart-steaming	Reduce the sea CO_2 intensities per ton/km by reducing energy consumption at lower speeds and minimising wait times at ports. This impacts mode choice and route choice	33% of TKM	20% of TKM

Carbon pricing

Carbon tax, green taxes and fuel taxes are different forms of taxes that can be applied to the aviation sector and are connected with the use of fuel or the fuel-burn resulting emissions. The main difference between these different forms of taxes is whether they are applied per litre of fuel or per tonne of CO_2 emitted. It is also important to note that fuel taxes for jet fuel are already in place in many parts of the world. Currently, fuel tax measures can be applied unilaterally by a country for its domestic flights or with a bilateral agreement for international flights between two countries. The CO_2 benefits of fuel or carbon taxes come mainly from demand reduction (ITF, 2023).

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Model implementation

This measure is introduced in the model by varying the unit cost for each mode. It can be based on the additional cost per vkm or tkm (based on the estimated load factor by commodity) by mode when a carbon tax is in place. This measure affects the mode choices and route choices. The implemented carbon pricing per ton is based on the reference literature (see e.g., Baranzini et al., 2017; Carbon Pricing Leadership Coalition, 2018).

Congestion or distance-based charges

Congestion pricing sets a price for road travel with the objective of reducing congestion and the time losses and adverse environmental impacts that it entails. Congestion pricing can be variable (the price is fixed at different levels during different time periods) or dynamic (the price changes in real-time according to monitored traffic levels). Congestion pricing can also apply to specific city zones (e.g. in London), roads (e.g. the cordon/ring road in Stockholm) or segments of urban highways (e.g., tolled express lanes in the US) (ITF, 2023).

Road pricing/charging is an old instrument widely used as a scheme to fund specific infrastructure realisation: the toll has to be paid by the users of the infrastructure (which can be a motorway, bridge, tunnel, etc.). The infrastructure perimeter has to be clearly defined. In Europe, road pricing is subject to regulation and law for trucks (see the Eurovignette Directive) (ITF, 2023).

Charges can reflect all the costs related to the infrastructure: construction, maintenance, operation, and all the externalities associated with its utilisation. Charges can vary depending on the category of vehicles: light or heavy / number of axels, Euro Norm of Emission, or some other characteristics. The charge can also vary according to the time of day/year in order to reflect congestion level (and associated externalities). For distance-based charging, there can be a per kilometre charge only or a per km charge with an additional base charge. For decarbonising transport, what is most important is to apply variation according to the emissions of the vehicles. This needs an additional system (the vehicle needs a label, like Eurovignette or Crit'air) to be put into place (ITF, 2023).

Model implementation

This measure may be introduced by affecting the cost of road freight activity. This cost increase will affect modal split but also route choice, as the trade between distance and time spent in travel may change.

Slow and smart steaming

Slow steaming is the practice of reducing maritime vehicle speeds. By operating ships at significantly slower speeds than their maximum speed, less fuel is consumed. This results in reduced CO_2 emissions. Slow steaming has been widely adopted since 2007, mainly due to the increased fuel costs at the time. Different ship types benefit differently from slow steaming (ITF, 2023). Besides financial benefits, regulation of ship speeds could also be used to encourage slow steaming. There is also a possibility of using fuel levies to induce slow speeding through the increases in fuel prices (OECD/ITF, 2018).

Model implementation

This measure yields significantly reduced CO_2 emissions. A speed reduction of 10% translates into an engine power reduction of 27% (Faber et al., 2017). Lower speeds are more effective if ship design speeds of ships are also lowered (Lindstad et al., 2011). The only potential adverse effect may result from the increased travel time that will affect the transport cost of some commodities that may decide the change for faster transport alternatives (e.g., road and rail). This measure has already been tested by Halim et al. (2016).

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Electric road infrastructure

Electrification of heavy-duty vehicles is more challenging than for their lighter counterparts due to the weight of the vehicle and the distances they cover. A battery sufficient to provide the necessary power is likely to have a significant impact on the possible payload for the vehicle, negatively impacting operational efficiency. Electric road infrastructure would overcome this by providing dynamic charging to moving vehicles. Studies suggest some level of uptake by 2050, but this will vary geographically. It will largely be dependent on the political will to decarbonise the sector and the available alternatives. Investment of public funds will be required for the initial development of the network, as a minimum level of coverage would need to be achieved before operators would consider electrifying their fleets. International co-operation for cross-border routes would also be required to ensure interoperability (*ITF Transport Outlook 2019*, 2019).

Model implementation

The impact of electric roads was implemented in the model by changing road costs based on IEA assumptions for their New Policy Scenario (NPS) (IEA, 2018a), affecting modal choice. This measure leads to a 37% reduction in carbon intensity in countries where the main network is equipped with electric road infrastructure. The level and timeline of implementation are differentiated by region. All relevant assumptions are based on (Cambridge Econometrics, 2018; ITF, 2018; Kasten, Mottschall, Köppel, & Degünther, 2016; Kühnel, Hacker, & Wolf, 2018; Schulte & Ny, 2018; Siemens, 2017).

Platooning

Platooning or platoons refers to convoys of semi-automated vehicle convoys linked via vehicle-to-vehicle communication systems and is regarded as a forerunner to autonomous trucks, as it is already in advanced testing. In an expert survey carried out by the ITF, a majority of respondents estimated the cost reduction potential of platooning at 10% or more. Truck platooning can decrease the wind drag of vehicles driving closely packed in a column and thereby increase fuel efficiency. But its benefits are more associated with the reduction of operational costs (*ITF Transport Outlook 2019*, 2019). In future, policy measures that increase the cost of operating road freight, such as distance-based charging and carbon tax, could encourage the uptake of platooning to reduce costs.

Model implementation

This measure is implemented in the model as a reduction of carbon intensity per vkm for vehicle activity in the main network of countries where this measure may be implemented. The implementation schedule of such a measure varies by region and prevalence of highways in the overall road network of the country. A proportion of vkms being operated under platooning leads to a reduction in the total CO_2 intensity. The reduction in CO_2 intensity was 14%. This assumption was derived from previous work at the ITF (ITF, 2017b).

Autonomous vehicles

Autonomous vehicles are a highly disruptive technology that could bring substantial changes in lifestyles, car ownership, travel patterns, land use, etc. Therefore, authorities and policy makers are facing the great challenge of designing standards, legislation and policies which could help to minimise risks, alleviate the negative effects and amplify the positive ones.

Authorities should provide legal clarity regarding the rights, obligations and liabilities of autonomous vehicle developers, operators, owners and insurance companies. This will include conditions under which

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developers can test and market the vehicles, criminal and civil liability rules and legal status for all the stakeholders, etc. (ITF 2015). On the operation side, the legislation will have to define the liability of drivers, passengers and vehicles in different situations (such as physical damage to a person or property, personal data leak or if a vehicle is used as a weapon of terror or for a crime), for an occupied and unoccupied vehicle. The insurance structure and compensation in case of an accident should also be defined.

Finally, the authorities will have to internalise the costs of driving as much as possible and stimulate individuals, companies and organisations to own and operate the vehicles in a way which would allow for reducing both direct and external societal costs, encouraging sharing rather than individual use of the vehicles (*ITF Transport Outlook 2019*, 2019).

Model implementation

This measure is implemented in the model as a cost reduction for road freight activities, resulting in potential changes to mode shares in freight transport. It is assumed the reduction of the driver costs is greater than the increases in cost stemming from the technology and the vehicle (reducing by around 45% of current values). This implementation is assumed to differ by geographical region. Carbon intensity per vkm is estimated to decrease by 14%. These assumptions were derived from (Bagloee et al., 2016; ITF, 2015, 2017b, 2018; NRC, 2010).

Operation of shared assets

Sharing assets, i.e. information flows, transport mechanisms or stocking spaces, can promote efficiency in resource management for logistic activities. One same enterprise, or several of them, can benefit from this sharing of assets. ICTs have only facilitated asset-sharing by decreasing information costs and providing platforms where various actors can share their assets. From an environmental point of view, sharing assets can increase logistic efficiencies, for instance, by increasing the occupancy rate of vehicles. Multimodality towards less carbon-intensive modes is also a possibility. Ultimately, improvements can reduce the number of trips required to deliver products, thus reducing the number of emissions linked to logistic activities. Asset sharing can also bring additional benefits. Costs for enterprises can be reduced by increasing efficiencies, for instance, by decreasing fuel consumption. Improvements linked to asset-sharing measures will be dependent on the types of activities led by the enterprises that decide to share assets. As an illustration, it will be harder to share transport assets between one enterprise transporting food and another one transporting industrial goods because of the difference in stocking needs for these products. Governments may need to consider appropriate competition regulation to facilitate such asset sharing and may need to consider how such actions could be enabled (e.g., through digital platforms) (ITF, 2023).

Model implementation

This measure is implemented by adapting the load factor for each commodity type in each travel mode. The reference values used for different scenarios are based on the efficiency increases introduced by the IEA MoMo model in the different scenarios (IEA-NPC and IEA-EV30@30) (IEA, 2018a).

Fuel economy standards – for vehicles and fuel

A low carbon fuel standard (LCFS) is a market-based policy mechanism aiming to reduce the life-cycle greenhouse gas (GHG) emission intensity of transportation fuels/energy vectors.

The mechanism is grounded on the definition of progressively tightened regulatory thresholds/limits for the average life-cycle (i.e. including production, distribution and use) GHG emission intensity of transport fuels/energy vectors (typically gasoline, diesel oil and jet kerosene) distributed by regulated parties

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(typically fuel suppliers and/or other entities that produce, import, distribute or sell transportation fuels). Fuels with a carbon intensity that is lower than the regulated threshold generate credits; fuels with higher GHG emission intensity generate deficits. In any given year, regulated parties need to have enough credits to compensate for any deficits created by the sale of carbon-intensive fuels. Regulated entities can trade credits and use credits banked from previous years to ensure they meet the policy requirements in any given year.

Mandatory vehicle efficiency standards require newly registered vehicles to emit less tailpipe CO_2 emissions than a specified threshold value (usually specified in gCO_2/km or similar) by a certain target date. Alternatively, such standards may be expressed as fuel economy standards that require vehicles to surpass a certain fuel-efficiency value (usually provided in miles/gallon fuel or similar). A vehicle's tailpipe CO_2 emissions and fuel consumption are typically assessed in standardised laboratory vehicle test procedures (ITF, 2023).

Model implementation

This measure is implemented in the model as a reduction of carbon intensity per vkm for the road sector, with a calendar of development by vehicle type and region in the ITF fleet model.

Low-carbon fuels

The development and availability of low or zero-carbon fuels for use in long-haul freight would be the outcome of multiple policy levers, including standards to create the need for an alternative, and likely incentives for research and development and for the uptake of alternative fuels, which may currently be more expensive than the existing fossil fuel. The adoption of low-carbon fuels would reduce the CO_2 emitted per vehicle kilometre (vkm) (ITF, 2023).

The development of low-carbon fuels for long distances can be encouraged through regulatory policy measures such as fuel economy standards and fuel blending mandates or through reducing investment risks for research and development in alternative fuels. A number of financial measures involve the public sector assuming risks that would otherwise need to be borne by private investors. Key examples include (ITF, 2023):

- the availability of financing from public entities at low-interest rates;
- loan guarantees, i.e., the obligation by the public sector to pay some or all the debt in the event the investor fails to pay;
- debt service reserves, i.e., deposits of cash to pay interest and principal payments in case a borrower fails to make scheduled payments;
- subordinated debt, where a public agency agrees to allow a lower priority position than senior debt holders (in case of default, senior debt holders are paid in full before other debt holders are repaid);
- the provision of grants by public agencies to investors to preserve or reduce the market interest rate of a loan;
- credit insurance products for bond financing, i.e. insurances agreeing to pay a bond in the event that a payment default occurs by the issuer; and
- Public Private Partnerships (PPPs), where the commercial risk is shared amongst private partners and the public sector.

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Model implementation

This measure is introduced into the model by changing the costs for road-based transport activity based on the IEA assumptions for their New Policy Scenario (IEA-NPS) (IEA, 2018a), thereby affecting modal choice. This measure also leads to a reduction in carbon intensity. The level and timeline of adoption are differentiated by region. All these assumptions are based on (Cambridge Econometrics 2018; ITF, 2018; Kasten, Mottschall, Köppel, & Degünther, 2016; Kühnel, Hacker, & Wolf, 2018; Schulte & Ny, 2018; Siemens, 2017).

Consolidation centres and platform sharing

Distribution centres allow for the consolidation of shipments from multiple suppliers and thereby optimise the loading of trucks onwards from the centre, improving the efficiency of the supply chain. This results in a reduction in vehicle kilometres and kilometres of empty running. Consolidation centres can also facilitate mode shift as it favours the transport of high volumes along main corridors, and trucks are required only for the first and last legs, thus reducing the vehicle kilometres operated on road.

Policies that encourage more efficient freight transport, such as distance-based charging and carbon taxes, as well as access restrictions on trucks in cities, can encourage the use of distribution centres as they can aid operators in reducing costs.

Model implementation

This measure affects the average load factors of surface transport modes (road and rail) that connect the main regional freight centres to urban consumption centres. It will also affect the average weight of, or space used in, each truck. Moreover, the use of a common platform to organise transport and measure activity has also been reported as a very cost-effective measure that companies are increasingly using (Li and Yu, 2017). The load factor gains are mainly linked with freight for typically less consolidated manufacturing goods that operate in a peer-to-peer manner or individual logistics chains of companies (e.g. textile and electronics). Load factor gains can be reflected in the conversion of tkms to vkms for each commodity type, and the load factor gain scenarios may vary by world region and target year. Values implemented can be based on existing literature on the topic, e.g., Ballot and Fontane, 2010; Ülkü, 2012.

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'High-with-Low' freight model outputs and discussion

This section presents illustrative outputs of the freight model. The results presented stem from the model runs developed to assess the 'High with Low' scenario narrative designed by the EDITS research network. The Current Ambition (CA) scenario developed within the forthcoming ITF Outlook 2023 represents a future where current political commitments and reasonable technological developments take place throughout the study period (2019-2050). The 'High-with-Low' scenario represents a more equitable future where energy and material consumption is lower than at present. Two variations of the High-with-low scenario are considered:

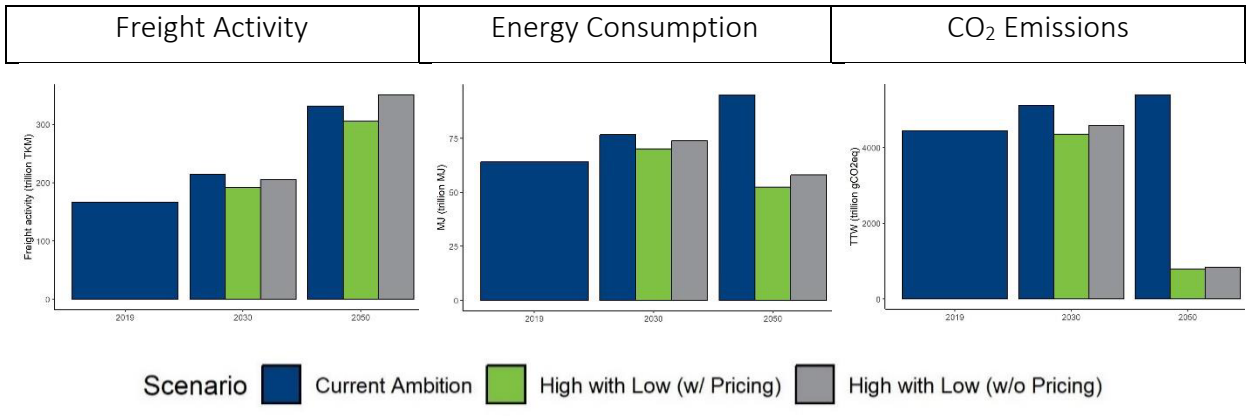
- 'High-with-Low w/o Pricing': meets the High-with-Low criteria but without additional pricing measures as per the Current Ambition scenario;
- 'High-with-Low w/ Pricing': meets the High-with-Low criteria implementing pricing measures.

The primary model outputs of the non-urban freight model are volumes of freight activity in tkm and the related energy consumption and CO_2 emissions by origin-destination (OD) pair, mode, and link.

At the global scale, the high-with-low scenario is not projected to decrease freight activity (measured in tkm) by 2050 unless pricing measures are included (Figure 7). However, the associated energy consumption and emissions would be significantly lower than the current ambition in the 'High-with-Low' scenarios with or without pricing measures. If pricing measures are included, energy consumption and associated CO_2 emissions will be lower by 2050.

Both 'High with Low' scenarios represent a significant activity increase from 2019 to 2050 (more than 80%) with a large CO_2 emissions reduction (more than 70%). This results shows, that even in a demand control context, it will be technology and operational efficiency the largest contributors to carbon mitigation.

Figure 7. Projected freight activity, and associated energy consumption and CO_2 emissions by scenario to 2050



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Regional outputs and comparisons

The global results can be further disaggregated into the reporting regions of the EDITS project. Namely: the Global North, Latin America, the Middle East and Africa, Asia (not including China), and China.

These results (Figure 8, Figure 9, Figure 10, Figure 11) highlight that the different regions have very different starting points. Therefore it is important to consider regional-specific measures that are more focused on particular regions in order to ensure equitable outcomes.

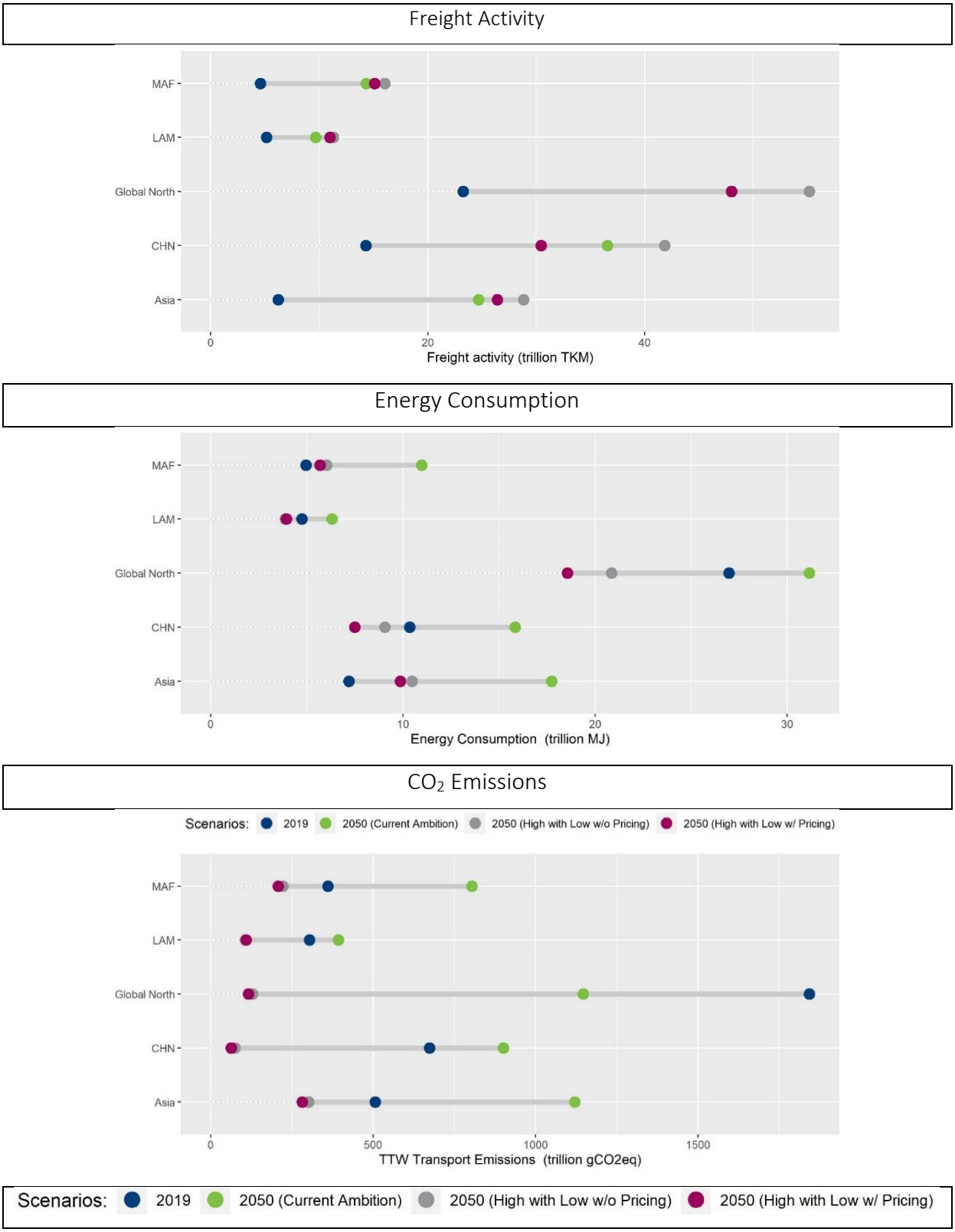
Another salient point that comes to light is the significant shares of activity, energy consumption and emissions which take place in International waters. How these are dealt with will be an important component of any global decarbonisation strategy.

Although the largest share of activity takes place in international waters (Figure 9) due to the scale of maritime shipping, the largest shares of energy consumption (Figure 10) and emissions (Figure 11) can be found in the Global North. Focused policies in the High-with-Low scenario, particularly when pricing is included, can significantly decrease emissions without large decreases in activity levels. The share of emissions by region varies over time and some Global South regions increasing significantly. Yet, the Global North keeps generating the largest share.

Worth nothing also the decrease overtime of international water freight activity, resulting from the reduction of fossil fuels trade, that account currently about 40% of maritime freight activity, and a boost of freight regional activity.

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Figure 8. Projected differences in freight activity (TKM), energy consumption (MJ) and emissions (TTW) by scenario and region to 2050



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Figure 9. Projected freight activity (ton kilometres) and shares by scenario & region to 2050

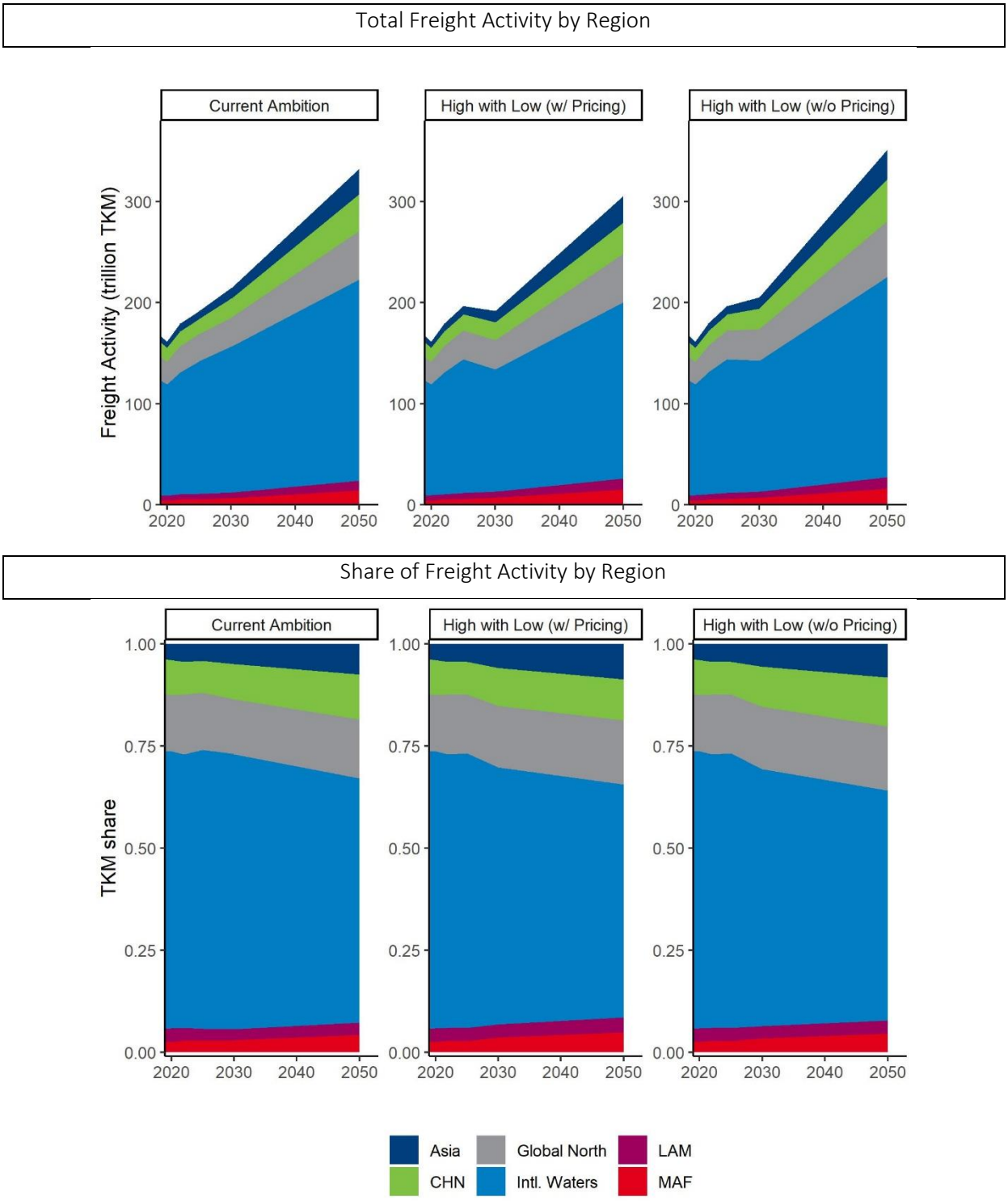
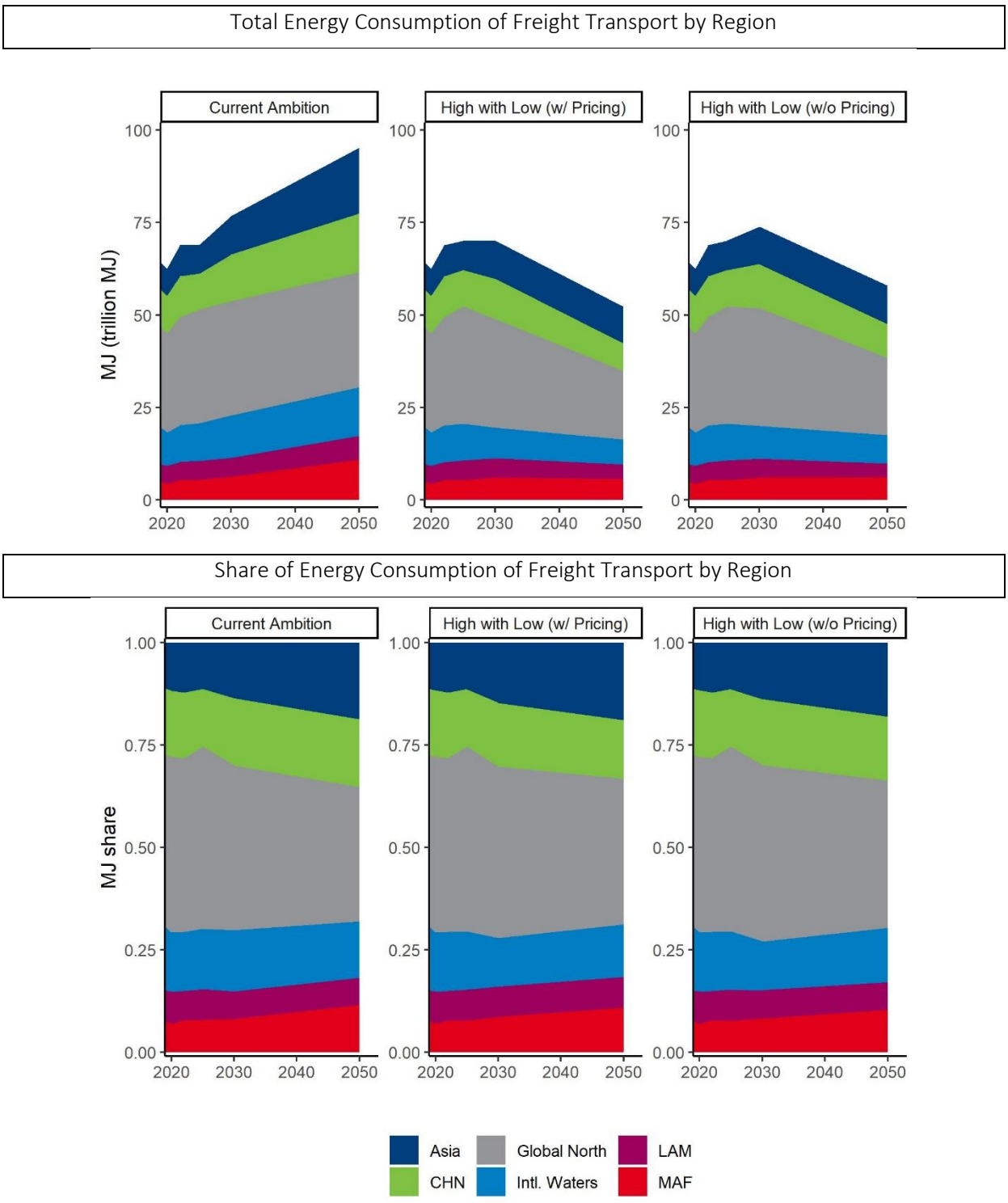
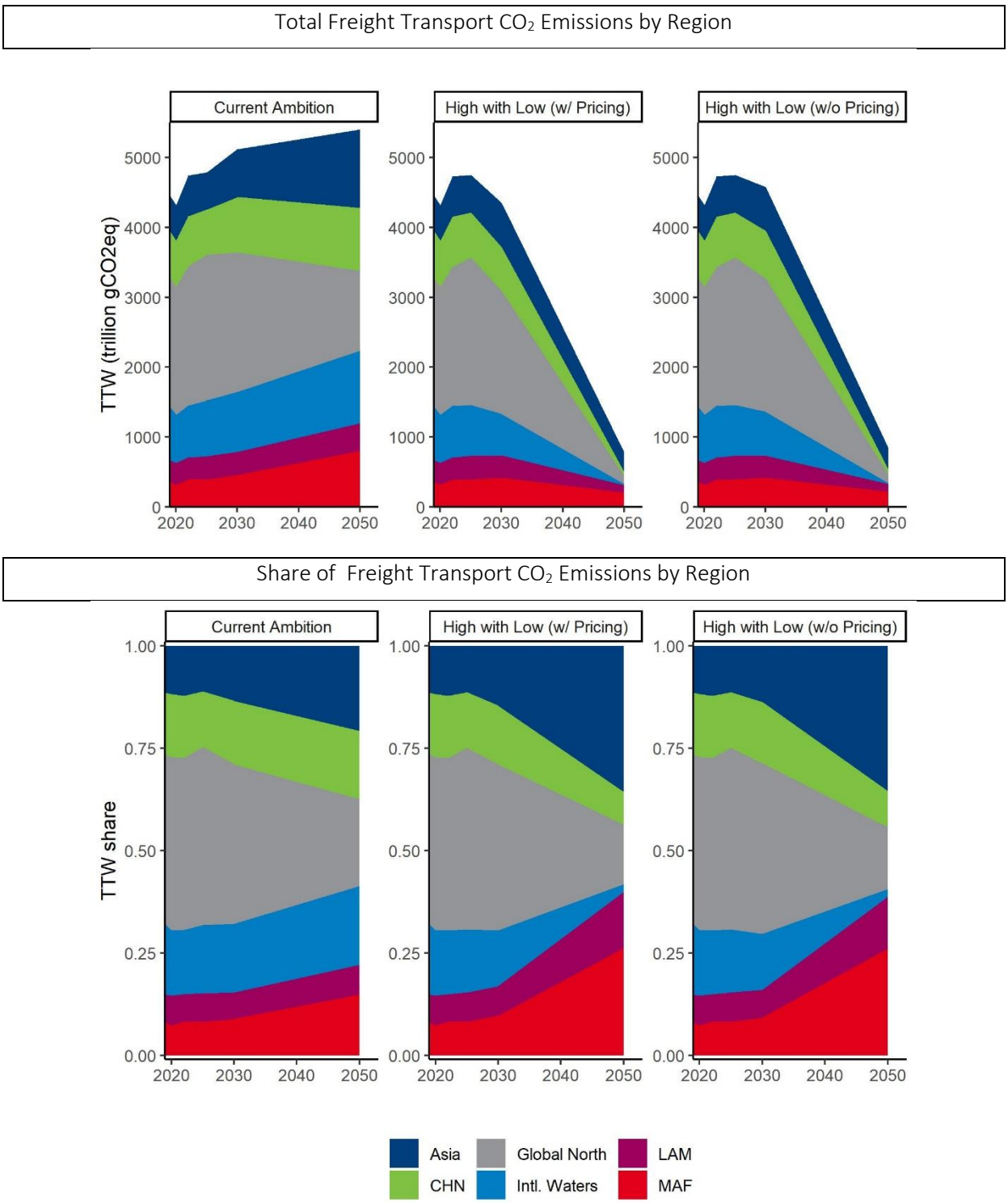


Figure 10. Projected energy consumption (MJ) and shares by scenario & region to 2050



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Figure 11. Projected associated CO2 emissions and shares by scenario & region to 2050



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References

", *ITF Transport Outlook 2019*" (2019), OECD, https://doi.org/10.1787/transp_outlook-en-2019-en.

Bagloee, S. A., M. Tavana, M. Asadi and T. Oliver (2016), "Autonomous vehicles: challenges, opportunities, and future implications for transportation policies", *Journal of Modern Transportation*, Vol. 24/4, pp. 284–303, https://doi.org/10.1007/s40534-016-0117-3.

Ballot, E. and F. Fontane (2010), "Reducing transportation CO2 emissions through pooling of supply networks: perspectives from a case study in French retail chains", *Production Planning & Control*, Vol. 21/6, pp. 640–650, https://doi.org/10.1080/09537287.2010.489276.

Baranzini, A., J. C. J. M. van den Bergh, S. Carattini, R. B. Howarth, E. Padilla and J. Roca (2017), "Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations", *Wiley Interdisciplinary Reviews: Climate Change*, , https://doi.org/10.1002/wcc.462.

Bottom, J., M. Ben-Akiva, M. Bierlaire, I. Chabini, H. Koutsopoulos and Q. Yang (1999), "Investigation of route guidance generation issues by simulation with DynaMIT", *Transportation and Traffic Theory*, pp. 577–600.

Cambridge Econometrics (2018), *Trucking into a Greener Future*, .

Carbon Pricing Leadership Coalition (2018, March), "What is carbon pricing?", accessed on 28, https://www.carbonpricingleadership.org/what/ (accessed .

Chateau, J., R. Dellink and E. Lanzi (2014), "An Overview of the OECD ENV-Linkages Model: Version 3", in *OECD Environment Working Papers, No. 65*, , https://doi.org/10.1787/5jz2qck2b2vd-en.

Chateau, J., L. Fontagné, J. Fouré, A. Johansson and E. Olaberría (2014), *Trade Patterns in the 2060 World Economy*, OECD Economics Department Working Papers, No. 1142, OECD Publishing.

CIESIN - Columbia University (2018), "Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11", NASA Socioeconomic Data and Applications Center (SEDAC).

Drewry (2013), *Global Container Terminal Operators Annual Review and Forecast 2013*, *Global Container Terminal Operators Annual Review and Forecast 2013*, .

Faber, J., Thomas Huigen and D. Nelissen (2017), *Regulating speed: a short-term measure to reduce maritime GHG emissions*, CE {Delft.

Grubler, A., G. Nemet, S. Pachauri and C. Wilson (2022), *The "High-with-Low" Scenario Narrative: Key Themes, Cross-Cutting Linkages, and Implications for Modelling EDITS WG3 Narratives group* (No. Draft May 27, 2022), .

Halim, R. A., J. H. Kwakkel and L. A. Tavasszy (2016), "A scenario discovery study of the impact of uncertainties in the global container transport system on European ports", *Futures*, , https://doi.org/10.1016/j.futures.2015.09.004.

ICAO (2018), *Annual Report of the Council 2017*, .

IEA (2018a), *Global EV Outlook 2018*, Paris, https://doi.org/10.1787/9789264302365-en.

IEA (2018b), *World Energy Outlook 2018*, Paris, https://doi.org/https://doi.org/10.1787/weo-2018-en.

© OECD/ITF 2023

ITF (2023), "Catalogue of Measures", Decarbonising Transport Initiative, https://www.itf-oecd.org/decarbonising-transport (accessed January 1, 2023).

ITF (2021), *ITF Transport Outlook 2021* (ITF Transport Outlook), OECD, Paris, https://doi.org/10.1787/16826A30-EN.

ITF (2020), *The ITF non-urban freight transport model - Insights and example outputs*, .

ITF (2018), *Towards Road Freight Decarbonisation Trends, Measures and Policies*, International Transport Forum.

ITF (2017a), "Goods transport", , https://doi.org/https://doi.org/https://doi.org/10.1787/g2g5557d-en.

ITF (2017b), *Managing the Transition to Driverless Road Freight Transport*, Paris.

ITF (2016), *Capacity to Grow*, International Transport Forum, https://doi.org/https://doi.org/https://doi.org/10.1787/5jlwvz8jlpzp-en.

ITF (2015), *Automated and Autonomous Driving Regulation under uncertainty*, .

Kasten, P., M. Mottschall, W. Köppel and C. Degünther (2016), *Erarbeitung einer fachlichen Strategie zur Energieversorgung des Verkehrs bis zum Jahr 2050 Endbericht*, .

Kühnel, S., F. Hacker and G. Wolf (2018), *Oberleitungs-Lkw im Kontext weiterer Antriebs-und Energieversorgungsoptionen für den Straßengüterfernverkehr*, Berlin.

Kummu, M., M. Taka and J. H. A. Guillaume (2018), "Gridded global datasets for Gross Domestic Product and Human Development Index over 1990-2015", *Scientific Data*, Vol. 5, https://doi.org/10.1038/sdata.2018.4.

Li, Y. and Y. Yu (2017), "The use of freight apps in road freight transport for CO2 reduction", *European Transport Research Review*, Vol. 9/3, pp. 36, https://doi.org/10.1007/s12544-017-0251-y.

Lindstad, H., B. E. Asbjørnslett and A. H. Strømman (2011), "Reductions in greenhouse gas emissions and cost by shipping at lower speeds", *Energy Policy*, Vol. 39/6, pp. 3456–3464, https://doi.org/10.1016/j.enpol.2011.03.044.

Martinez, L. M., J. Kauppila and M. Castaing (2015), "International Freight and Related Carbon Dioxide Emissions by 2050: New Modeling Tool", *Transportation Research Record: Journal of the Transportation Research Board*, 2477, pp. 58–67.

NRC (2010), *Hidden Costs of Energy*, National Academies Press, Washington, D.C., https://doi.org/10.17226/12794.

OCS (2012a), *East Asian Containerport Markets to 2025*, Ocean Shipping Consultants.

OCS (2012b), *Middle East Containerport Markets to 2025*, (Ocea, Ed.), Ocean Shipping Consultants.

OCS (2012c), *North European Containerport Markets to 2025*, Ocean Shipping Consultants.

OECD/ITF (2018), *Decarbonising Maritime Transport Pathways to zero-carbon shipping by 2035*, .

OECD (2022), *OECD Economic Outlook*, OECD Publishing, Paris, https://doi.org/http://dx.doi.org/10.1787/eco_outlook-v2016-1-en.

OECD (2021), "ENV-Linkages model", in *The Economic Benefits of Air Quality Improvements in Arctic Council Countries*, OECD Publishing.

Schulte, J. and H. Ny (2018), "Electric road systems: Strategic stepping stone on the way towards

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sustainable freight transport?", *Sustainability (Switzerland)*, Vol. 10/4, https://doi.org/10.3390/su10041148.

Siemens (2017), *eHighway: Innovative electric road freight transport*, .

Smith, T. W. P., J. P. Jalkanen, B. A. Anderson, J. J. Corbett, J. Faber, S. Hanayama, … A. Hoen, M. (2014), "Third IMO Greenhouse Gas Study 2014", *International Maritime Organization (IMO)*, , https://doi.org/10.1007/s10584-013-0912-3.

Tavasszy, L., M. Minderhoud, J. F. Perrin and T. Notteboom (2011), "A strategic network choice model for global container flows: Specification, estimation and application", *Journal of Transport Geography*, , https://doi.org/10.1016/j.jtrangeo.2011.05.005.

Ülkü, M. A. (2012), "Dare to care: Shipment consolidation reduces not only costs, but also environmental damage", *International Journal of Production Economics*, Vol. 139/2, pp. 438–446, https://doi.org/https://doi.org/10.1016/j.ijpe.2011.09.015.

UN (2015), *World Population Prospects*, *United Nations*, (Vol. 1)United Nations, Department of Economic and Social Affairs, Population Division, https://doi.org/10.1017/CBO9781107415324.004.

UN Comtrade (2022), "UN Comtrade | International Trade Statistics Database", *UN Comtrade*, .

UN DESA (2022), *World Population Prospects 2022*, United Nations.

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The ITF fleet model: Part of the ITF PASTA framework

- Model framework, insights and outputs

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The project has received funding from the Research Institute of Innovative Technology for the Earth (RITE) under subcontract agreement D06710

Abstract

The ITF vehicle fleet model is used to estimate the evolution of vehicle fleets into the future based on historical fleet data, projected future demand for transport from the ITF demand modelling suite and scenarios of technology adoption. The ITF fleet model outputs the number of vehicles, energy use and CO_2 and air pollutant emissions over time.
The model includes estimates of the main outputs for nine global regions and the following vehicle types: Two and three-wheeled vehicles (2&3Ws), Passenger Cars, Buses, Light Commercial Vehicles (LCVs), Lorries, Road Tractors, Airplanes, Passenger Trains, Freight Trains and six different families of ships. The model does not currently distinguish between urban and non-urban vehicle fleets.

EDITS

Energy Demand changes Induced by Technological and Social innovations

Final Version Report

Report summarizing Tasks 1,2 and 3

Name of the institute responsible for the redaction of the report [a]

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

Author's name: Cristina Cattaneo, Yannik Stuka, Elena Verdolini

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International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

RITE Research Institute of Innovative Technology for the Earth

Executive Summary

This report summarizes the outcomes of three tasks related to the EDITS project. The project aims to (1) asses technological innovation on the energy demand side; (2) review social changes resulting from (1); (3) investigate further impacts on CO2 emission reduction; and (4) produce a comparative evaluation of scenarios with major global research institutions.

This report in particular addresses objective (1) by focusing on the industrial sector and innovation in 3D printing. The functions of the innovation system around 3D printing technologies are analyzed. We show that several key actors are involved in technology development and are being supported by public policy. Yet, 3D printing has currently achieved maturity and is applied only in a few phases of production, mostly linked with prototyping and customization. To ensure that 3D printing is scaled up and more widely applied in the context of a LED scenario, a few both technical and non-technical barriers need to be overcome. To ensure that Additive Manufacturing (AM) can contribute to LED narratives the following achievements will need to be reached: 1) the technology needs to mature, and proof-of-concept needs to be achieved for large-scale manufacturing; 2) business have to move away from traditional linear manufacturing and towards new models promoting on-demand production, and 3) the deployment of 3D technologies needs to be guided by social innovation, behavioral change, new mindsets and targeted policies to ensure that both economic benefits and societal goals are achieved, including deep emission reductions, circularity and sufficiency. If all these conditions occur, AM technologies could significantly reshape several economic sectors and their provision of goods and services, albeit differently in different sectors. For instance, AM could reduce Total Primary Energy Supply (TPES) in aerospace fuels by 9 to 35 percent, in aerospace manufacturing by 8 to 19 percent, in medical equipment by 5 to 19 percent and in medical tools by 3 to 10 percent.
This report also addresses objective (2) by looking at a behavioral intervention that boosts usage spillovers in residential buildings between water, electricity and natural gas. The investigation has shown that providing customers with a water report that compares own consumption with that of similar neighbors, significantly decreases water usage by 1.4%. It also decreases usage in a different domain, namely electricity, by 0.5% . For both water and electricity, the impact of the behavioral program is driven

by customers for whom the water report is the only one to be received. This suggests a saturation effect of multiple interventions on consumption. The gas and electricity reports, that customers received before the water intervention was launched, may have generated spillovers in water use, making additional water conservation harder. The water report also leads to higher customer retention. Treated gas and electricity customers are 2.8 and 3% less likely to deactivate their contract than control ones, respectively. Behavioral mechanisms seem to play a role whereby the water report makes environmental concerns salient, thus driving conservation efforts in other domains. Overall, our results suggest that, by promoting diversified and complementary information and marketing campaigns, companies can win customers' loyalty in a competitive market with increasing retention challenges, even though the impact on resource conservation of additional interventions is decreasing.

Finally, the report informs on objective (4) by focusing on global LED scenarios and their feasibility and desirability, assessing them in the light of a well-being framework. We suggest a framework focusing on the dimensions of health, decent living standards as well as security and stability. In order to evaluate different mitigation strategies, our framework aims to explore four scenarios that achieve the same climate target. Specifically, we are interested in the C1 category of scenarios that limit global warming to 1.5°C with no or limited overshoot. All scenarios lead to energy intensity improvements in all regions. Implementing low demand policies while following the Sustainable Development Pathways (SDP) would substantially decrease oil dependence in China and Europe. While Europe is projected to undergo a sharp decline in gas dependence in all scenarios, China increases its gas import dependence along SDP and Net Zero Pathways. These findings suggest that natural gas might play a pivotal role in certain mitigation pathways. Given the current geopolitical situation and concerns surrounding reliance on natural gas, it is imperative to examine whether equally ambitious climate objectives can be accomplished with reduced global reliance on natural gas. We observe that all scenarios show declines in energy consumption levels in the transport sector, particularly in developed regions like North America and Europe. However, the SDP scenario projects a more rapid and substantial decline in the developed regions. This implies that there is regional convergence in the provision of mobility services around the decent living threshold in the SDP scenario. The SDP

scenario projects significant improvements in the energy efficiency of buildings, especially in developed countries, but also in China beyond 2050. We observe a considerable increase in available floor space in China and India, while developed regions maintain their current levels until the end of the century. The SDP scenario assumes a significant reduction in food consumption and waste, particularly in developed regions but displaying noteworthy differences.

Review of system-wide industry modelling approaches for low energy and materials demand scenarios

Deliverable about the current results from the EDITS Industry Working Group. 28.2.2023

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Abstract

Sustainable development and climate change mitigation require a deep structural transformation of global industrial production to rapidly reduce industry's multiple environmental impacts. Industry also needs to transform to meet rapidly changing demand patterns for industrial output required for sufficient service provision and societal wellbeing around the world. Model-based insights are crucial for effective policy design and evaluation, to enable and support such an industrial transformation.

In this reviewing effort, we take an integrated and comprehensive demand-supply perspective on the industrial transformation. We review the growing number of recent studies and modelling approaches, which explore transformative low energy and low-materials demand (LEMD) scenarios towards net-zero GHG emissions. We synthesize key principles and crucial considerations for LEMD scenarios with high service provision and wellbeing, which should ideally be addressed by industry modelling to fully show the potentials of supply and demand-side strategies. Via an expert-driven process, we identify and review eight modelling traditions which operate at a scale and scope necessary for LEMD modelling, which are equilibrium/neo-classical economics, non-equilibrium/post-keynesian economics, partial equilibrium modelling, macro-econometric forecasting, environmentally extended input-output analysis, life cycle analysis, material and energy flow analysis, system dynamics, agent-based modelling, as well

Report Title - The Impact of Digital Consumer Innovations: An Analysis of Variance between the Emissions Benefits of Digital Consumer Innovations

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1. Introduction

There is broad consensus that replacing high emission products and services with digital consumer innovations can reduce consumer-based emissions in line with the Paris Climate agreement [3]. Studies estimating the emissions benefits (herein referred to as *'benefits'*) of digital consumer innovations vary in methodological approach which can lead to statistical variation in the size and direction of estimates [2, 8]. This makes direct comparison between study outcomes difficult and potentially invalid.

Meta-analysis is a rigorous methodology which enables 'effect sizes' from individual empirical studies to be compared and contrasted. It involves a number of techniques which if appropriate include the pooling of effect sizes to derive overall conclusions [2]. Here an effect size is defined as "a quantitative reflection of the magnitude of some phenomenon that is used for the purpose of addressing a question of interest." [5, p. 140].

A quantitative synthesis of the *'benefits'* of specific digital consumer innovations could improve the accuracy and granularity of global models of the energy system by providing empirically based comparison points for modelled outcomes; it could generate insights into the relative interdependencies of outcomes of digital consumer innovations (disruptive effects); and it could set the scene for further quantification of related effects such as 'induced-demand' and 're-bound' effects [4, 6, 7].

In this report we present the findings of a first stage of meta-analysis. This consists of an exploratory, quantitative analysis using estimates of the (emissions related) '*benefits*' across a range of digital consumer innovations, derived from two key synthesis publications. These two studies collectively provide 141 independent estimates for 23 different digital consumer innovations across the domains of transport, food, and homes. These emissions related '*benefits*' are standardised metrics of percentage change related to one of three outcomes: (i) changes in activity levels (e.g., less frequent car use); (ii) changes in CO_2 emissions (e.g., from switching to locally sourced food); (iii) changes in energy use (e.g., reducing electricity use in the home). All potential *'benefits'* relate to the use or adoption of digital consumer innovations.

This report is structured as follows. First, we measure and explain broad heterogeneity between the size and direction of estimates of *'benefits'*. We use both parametric and non-parametric approaches. Second, we measure and explain heterogeneity between pooled estimates of *'benefits'* for each type of digital consumer innovation. We use parametric approaches including Ordinary Least Squares bivariate regression, and grouped, conditional regression.

Aim and Objectives of this Report

The over-arching aim of this report is to evaluate the suitability of available data for further meta-analysis techniques. Meta-analysis would involve the creation of valid and reliable estimates for each digital consumer innovation.

This report has two main objectives:

(1) To identify sources of statistical variation between estimates of the *'benefits'* of digital consumer innovations

(2) To evaluate the extent to which pooling of these estimates could create valid and reliable measures of the '*benefits*' of digital consumer innovations.

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We test five key hypotheses:

- H1 Estimated *'benefits'* vary according to the type of digital consumer innovation
- H2 Studies that estimate larger *'benefits'* are more likely to have lower internal validity/robustness
- H3 Studies that estimate larger *'benefits'* are more likely to have lower external validity/generalisability
- H4 Emissions '*benefits*' estimated from changes in activity are larger than those estimated from changes in energy or carbon emissions
- H5 Estimated emissions '*benefits*' are larger in simulations than in empirically based approaches

2. Materials and Methods

2.1 Identification of studies suitable for meta-analysis

We use data taken from two key publications both are synthesis studies containing multiple estimates of the emissions related '*benefits*' of digital consumer innovations:

1. Potential Climate Benefits of Digital Consumer Innovations. Wilson C., Kerr L., Sprei F., Vrain E. (2020). Annual Review of Environment and Resources, Volume 24, pages 113-144 (N=126 estimates)

2. Chapter 5, Demand, Services and social aspects of mitigation, the contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Creutzig, F., J. Roy, P. Devine-Wright, J. Díaz-José, F.W. Geels, A. Grubler, N. Maïzi, E. Masanet, Y. Mulugetta, C.D. Onyige, P.E. Perkins, A. Sanches-Pereira, E.U. Weber, 2022: Demand, services and social aspects of mitigation. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.007. (N=18 estimates).

Across these studies we extract 141 estimates '*benefits*' for 23 different digital consumer innovations. See Appendices 1 and 2 for full list of studies.

2.2 Preparation of data

Our approach is systematic and robust. From each study we extract quantitative estimates of the potential *'benefits'* of digital consumer innovations. All estimates measure % change (%Δ) from the adoption/use of a digital consumer innovation compared to a baseline measurement. Emissions benefits relate to one of three types: (i) change in activity (%Δ activity (n=64)); (ii) change in CO_2 emissions (%Δ emissions (n=63)); (iii) change in energy (%Δ energy (n=54)).

Where studies include multiple point estimates across a range of values, we calculate the midpoint

as a representation of the mean. Around a third of studies contain multiple estimates due to different outcome metrics (energy; emissions), differing assumptions (e.g., 1 worker household, 2 or more worker household), or a variant on the innovation type (e.g., ride sharing in a conventional vehicle; ride sharing in an EV relative to no ride sharing). For completeness we include multiple estimates from these studies and treat them as independent estimates of '*benefits*'. Although there is some risk of covariance between variables measuring methodological approach, we do not treat the data as multi-level at this stage, because not all studies provide repeated measures.

To examine and compare variation in '*benefits*' we derive independent variables from each related study to measure five types of known statistical variation: (A) type of digital consumer innovation; (B) internal validity or robustness of the study; (C) external validity or generalisability of the study; (D) '*benefits*' type and (E) analytical method. In Table 1 we define these variables and related metrics. Variable labels are also defined and used as a short-cut reference in modelling approaches.

Table 1 Sources of methodological variation between studies

Source of methodological variation	**Variable Label**	**Definition**	**Metric**	**Metric Label**
A. Type of digital consumer innovation	'inn'	Digital consumer innovations are digitally enabled goods or services which provide alternatives to mainstream practices of consumption, with potential relevance to climate change mitigation. A set of 23 consumer innovations are considered around three domains of consumption activity.	Domain[1]: Transport (T) Food (F) Homes (H)	'T1'-'T11' 'F1'-'F6' 'H1'–'H8'
B. Internal validity / robustness	'rob'	A measure of the strength of the study design for making robust inferences about the effect sizes. The assessment relates to methodological transparency and assumptions, the use of randomised controls, type of data (e.g., observed, or self-reported behaviour), and whether a sensitivity analysis has been undertaken.	High Medium Low	'robH' 'robM' 'robL'
C. External validity / generalisability	'gen'	'Generalisability' or external validity is the wider applicability of the results. This measure considers self-selection bias, sample size, heterogeneity, and whether field trails or natural experiments have been conducted.	High Medium Low	'genH' 'genM' 'genL'
D. Emissions related benefit	'outcome'	Consumption activity, energy use, or emissions of carbon dioxide (CO_2) associated with digital consumer innovations with potential emission-reduction benefits. Activity is the amount of activity or useful service consumed. Carbon is the amount of greenhouse gas emissions (CO_2 or CO_2-equivalent greenhouse gases) either in absolute terms or in relative terms. Energy is the amount of energy or resources needed to provide a useful service.	%Δ activity %Δ carbon %Δ energy	*'outA'* *'outC'* *'outE*
E. Analytical method	'meth'	Methodological approaches are categorised as '*accounting*' - the linear combination of disaggregated variables in a mathematical model (e.g., lifecycle analysis); '*empirical*' –	Accounting model Empirical	'methA' 'methE' 'methSE' 'methSM'

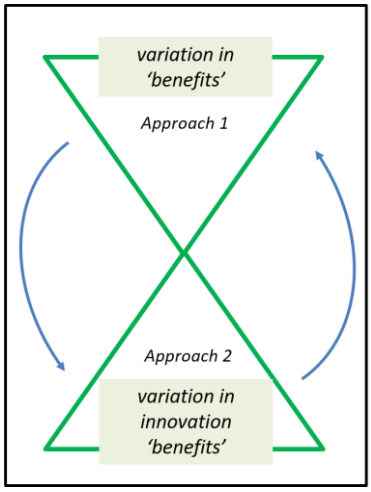
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		the collection of observed data through field trials, natural experiments, and demonstration projects; '*simple estimation*' - based on empirical or anecdotal evidence with broad assumptions and uncomplicated accounting; '*simulation'* - a digital parameterised model of a real-world system.	Simple estimation Simulation model	

[1] see Appendix 2 - List of digital consumer innovations

2.3 Analysis of Data

We take two approaches which differ in their focus. Approach 1 explores variation between the 141 undifferentiated '*benefits*'. Approach 2 explores variation in innovation differentiated '*benefits*' (see Figure 1).



In Approach 1 we examine and explain differences between the size and direction of '*benefits*' due to methodological variation. We use descriptive statistics and simple Ordinary Least Squares (OLS) bivariate regression. Descriptive tests compare median and mean differences. Tests include the use of 'terciles' to identify strong, moderate, and weak '*benefits*' estimates, and non-parametric (Kruskal Wallis Rank-sum) and parametric (ANOVA) tests to compare the significance of these. We use a series of five OLS models to test for explained variance (R^2) between (Y) the size and direction of '*benefits*' and (X) methodology. We test hypotheses H1-H5 (see Table 2). The generic model takes the following form:

$$Y = \alpha + \beta X_{AtoE} \qquad \text{[Equation 1]}$$

where *Y* = size and direction of emissions related benefit, X_{AtoE} = measures of methodological variation (defined in Table 1)

In Approach 2 we examine and explain variation between (Y) size and direction of emissions related '*benefits*' and (X) type of digital consumer innovation. To understand (and control for) variation both within and between methodological variation, we systematically test relationships within and across distinctive sub-samples of the data (see Table 2). We run a series of 'conditional' OLS models to test hypotheses H2 to H5. The generic model takes the following form:

$$Y = \alpha + \beta X \; if \; Z = B_{i-iii} to \; E_{i-iv} \qquad \text{[Equation 2]}$$

where *Y* = size of emissions related benefit, *X* = type of digital consumer innovation, Z= conditional variant of study methodology (B to E) (see Table 2).

Table 2 is a summary of the OLS models used across Approach 1 (models labelled M1) and Approach 2 (models labelled M2 to M5). To interpret the label 'short-forms' please refer to Table 1.

Table 2 – Summary of OLS Bivariate Regression Models

Model	Equation	H tested	Dependent Variable (Y)	Independent Variable (X)	Conditional variable (Z)	n	N
M1inn	[1]	H1	*'benefit'*	*'inn'*	n/a		141

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M1rob	[1]	H2	*'benefit'*	*'robust'*	n/a		141
M1gen	[1]	H3	*'benefit'*	*'gen'*	n/a		141
M1ben	[1]	H4	*'benefit'*	*'outcome'*	n/a		141
M1meth	[1]	H5	*'benefit'*	*'meth'*	n/a		141
M2robH	[2]	H2	*'benefit'*	*'inn'*	'robH'	9	
M2robM	[2]	H2	*'benefit'*	*'inn'*	'robM'	63	
M2robL	[2]	H2	*'benefit'*	*'inn'*	'robL'	69	
					Total N		**141**
M3genH	[2]	H3	*'benefit'*	*'inn'*	'genH'	25	
M3genM	[2]	H3	*'benefit'*	*'inn'*	'genM'	35	
M3genL	[2]	H3	*'benefit'*	*'inn'*	'genL'	81	
					Total N		141
M4outA	[2]	H4	*'benefit'*	*'inn'*	*'outA'*	24	
M4outC	[2]	H4	*'benefit'*	*'inn'*	*'outC'*	63	
M4outE	[2]	H4	*'benefit'*	*'inn'*	*'outE*	54	
					Total N		141
M5methA	[2]	H5	*'benefit'*	*'inn'*	'methA'	36	
M5methE	[2]	H5	*'benefit'*	*'inn'*	'methE'	33	
M5methSE	[2]	H5	*'benefit'*	*'inn'*	'methSE'	20	
M5methSM	[2]	H5	*'benefit'*	*'inn'*	'methSM'	52	
					Total N		141

3. Results

3.1 Results – Approach 1

In Table 3 we summarise mean and median *'benefits'* for each methodological variant, used as 'covariates' in this analysis. Figures highlighted in '**orange**' denote values which lie within the lower tercile range across the whole sample distribution. These have the greatest emissions '*benefits*'. They lie within the range %Δ '*benefit'*=-0.9999 to -0.34135 ie., reduction in emissions related benefit compared to the baseline. Figures highlighted in '**blue**' denote values which lie in the upper tercile range. These have the lowest emissions '*benefits*', and they lie within the range %Δ '*benefit'*=-0.1319 to +12.205.

Table 3. Emissions related '*benefits*' for key covariates

Covariates	N	Mean	Median
Innovation type		%Δ '*benefit'*	%Δ '*benefit'*
T1 Car clubs (or car-sharing in US)	11	-0.263	-0.301
T3 Ride-sharing (carpooling in US)	5	-0.134	-0.103
T4 Shared taxis	8	-0.294	-0.295
T5 Mobility-as-a-service	1	-0.139	-0.139
T6 Electric vehicles	6	**-0.563**	**-0.515**
T7 E-bikes	4	**-0.506**	**-0.491**
T8 Fully autonomous vehicles	9	-0.136	**-0.090**
T9 Neighbourhood Electric Vehicles	2	-0.155	-0.155
T10 Bike-sharing	4	**2.917**	**-0.034**
T11 Telecommuting	13	**0.029**	**-0.003**
T12 Videoconferencing & virtual interaction	10	**-0.529**	**-0.639**
F1 Digital hubs for local food	5	**0.008**	**-0.440**
F2 Meal kits (or meal boxes)	10	**0.070**	**-0.354**
F3 11th hour apps	2	-0.208	-0.208
F4 Foodpairing apps	1	-0.150	-0.150
F6 Food gamification apps	5	**-0.325**	**-0.340**
H1 Smart heating systems	5	-0.187	-0.216

H2 Smart lighting	5	**-0.375**	**-0.405**
H4 Smart home appliances & IoT	17	-0.194	-0.122
H5 Home energy management systems	5	**-0.337**	-0.300
H6 Heat pumps	2	**-0.770**	**-0.770**
H7 P2P exchange of goods	1	**-0.061**	**-0.061**
H8 Disaggregated real-time energy feedback	10	-0.115	-0.122
Internal validity / robustness			
High	9	-0.097	**-0.061**
Medium	63	**0.063**	-0.135
Low	69	-0.298	-0.219
External validity / generalisability			
High	25	**0.027**	**-0.085**
Medium	35	-0.146	-0.114
Low	81	-0.170	-0.223
Emissions related '*benefits*'			
%Δ activity	24	-0.203	-0.200
%Δ energy	54	-0.173	-0.183
%Δ CO_2 emissions	63	**-0.064**	-0.170
Analytical Method			
Accounting	36	**0.076**	-0.216
Empirical model	33	-0.211	-0.135
Simple estimation	20	-0.307	-0.185
Simulation	49	-0.151	-0.210

Blue = within highest tercile (lowest emissions benefit); dark orange = within lowest tercile (greatest emissions benefit)

Key Finding: Digital consumer innovations range between those that offer greatest emissions '*benefits*' (e.g., T6 electric vehicles, T7 E-bikes, T12 videoconferencing and virtual interaction, H6 Heat pumps) and lowest emissions benefits (e.g, T10 bike-sharing, F2 meal kits). There is less evidence of variability in the '*benefits*' estimates due to methodological variation.

For the remaining results in Approach 1, we report findings in table format (Tables 4(a) to 4(e) with a summary statement of level of support for the hypothesis.

H1 Estimated '*benefits*' vary according to the type of digital consumer innovation

Table 4(a) Tests related to innovation type

Type of analysis	**Key test results**
Kruskal Wallis test (ranksum test) for differences between the medians for three or more independent groups	chi2(22) Prob = 0.0001**
One-way analysis of variance with Scheffe multi-comparison of means	Prob > F = 0.0624
OLS Regression (Model M1inn)	R^2 = 22.76

Key Finding: There is strong support for H1. Parametric and non-parametric tests are both significant. OLS bivariate regression, suggests that over 22% of the variation between '*benefits*' is explained by innovation type.

H2 Studies that estimate larger '*benefits*' are more likely to have lower internal validity/robustness

Table 4(b) Tests related to robustness of study

Type of analysis	Key test results
Kruskal Wallis test (ranksum test) for differences between the medians for three or more independent groups	chi2(22) Prob = 0.0074**
One-way analysis of variance with Scheffe multi-comparison of means	Prob > F = 0.2291
OLS Regression (Model M1rob)	R^2 = 22.91

Key Finding: There is some support for H2. Non-parametric tests show significant variation between median levels of robustness, but parametric approaches are not significant. The ANOVA test used is however, sensitive to relative sample sizes. There are only nine estimates that have high levels of robustness (see Table 3). OLS regression suggests that study robustness explains nearly 23% of variation in the size of '*benefits*' estimates.

H3 Studies that estimate larger '*benefits*' are more likely to have lower external validity/generalisability

Table 4(c) Tests related to generalisability of study

Type of analysis	Key test results
Kruskal Wallis test (ranksum test) for differences between the medians for three or more independent groups	chi2(22) Prob = 0.0065**
One-way analysis of variance with Scheffe multi-comparison of means	Prob > F = 0.7590
OLS Regression (Model M1gen)	R^2 = 0.4%

Key Finding: There is weak support for H3. We find statistically significant differences in the medians for levels of external validity but otherwise no support for this hypothesis.

H4 Estimated '*benefits*' from changes in activity are larger than estimated changes in energy or carbon emissions

Table 4(d) Tests related to outcome type

Type of analysis	Key test results
Kruskal Wallis test (ranksum test) for differences between the medians for three or more independent groups	chi2(2) Prob = 0.8485
One-way analysis of variance with Scheffe multi-comparison of means	Prob > F = 0.8320
OLS Regression (Model M1ben)	R^2 = 0.27%

Key Finding: There is weak support for H4 in terms of mean and median differences. However, OLS regression suggests type of outcome explains 0.27% of the variation in the size of '*benefits*' estimates.

H5 Estimated '*benefits*' are larger in simulations than in empirically based approaches

Table 4(e) Tests related analytical method

Type of analysis	Key test results
Kruskal Wallis test (ranksum test) for differences between the medians for three or more independent groups	Method (long form): chi2(12) Prob = 0.2219
One-way analysis of variance with Scheffe multi-comparison of means	Method (long form): Prob > F = 0.9975
OLS Regression	Method (long form): R^2 = 2.32%

Key Finding: The evidence from the analysis of undifferentiated '*benefits*' provides no support for H5.

4.2 Results Approach 2

For Approach 2 we communicate main findings against hypotheses H2 to H5 as a series of graphs. In each graph we plot the post-estimated average emissions '*benefits*' for each digital consumer innovation across each level or category of methodological variant. These are predicted from models M2 to M5. We concentrate on two main criteria: differences in the size of '*benefits*'; and differences in the size of related '*standard errors*'. In this respect the standard error is used as an indicator of 'suitability' for wider representation of a given population mean. Smaller standard errors suggest the 'pooled' means are potentially more reliable [11]. In each graph we use different colours to denote domain type, such that blue=transport related innovation, green= food related innovation red=homes related innovation.

H2 Studies that estimate larger '*benefits*' are more likely to have lower internal validity/robustness

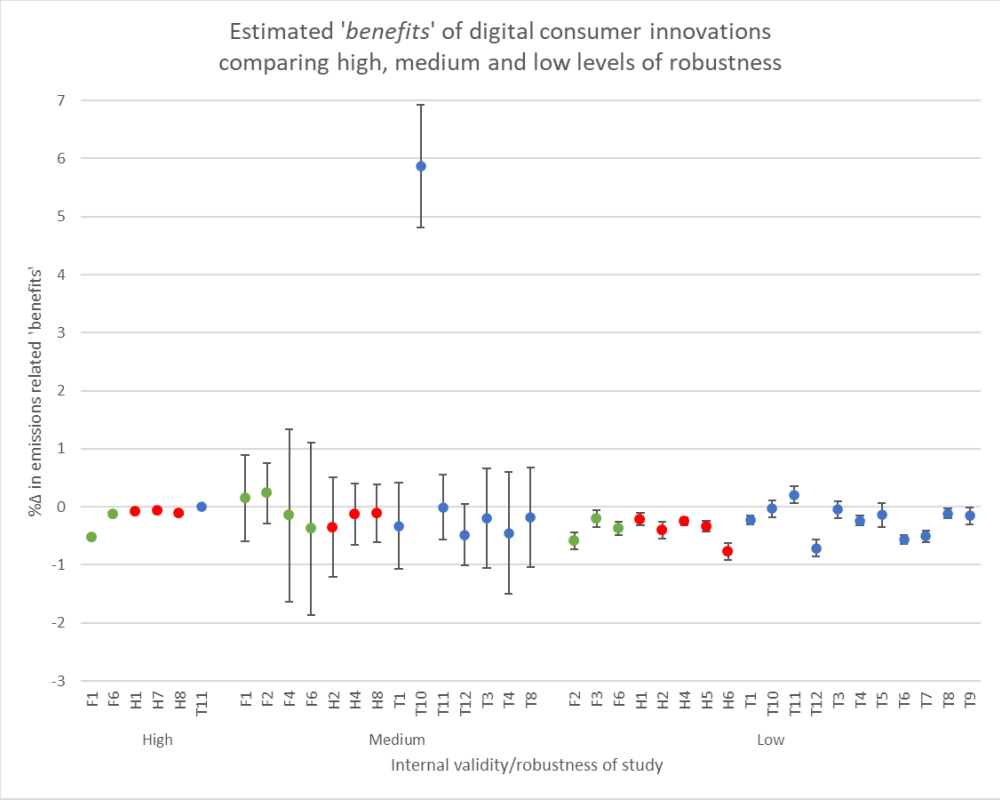


Figure 2 – '*Benefits*' of digital consumer innovations, comparing levels of robustness

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Key Finding: There is very weak support for H2. There is noticeably less variation in the size of 'benefits' for innovations with high levels of robustness. The overall mean effect size, however, is slightly larger for low relative to high robustness studies, but the smaller variation in standard errors at low robustness levels is unexpected. Study designs that are more rigorous and have higher internal validity would generally be expected to have smaller effect sizes and related standard errors [14].

H3 Studies that estimate larger '*benefits*' are more likely to have lower external validity/ or generalisability

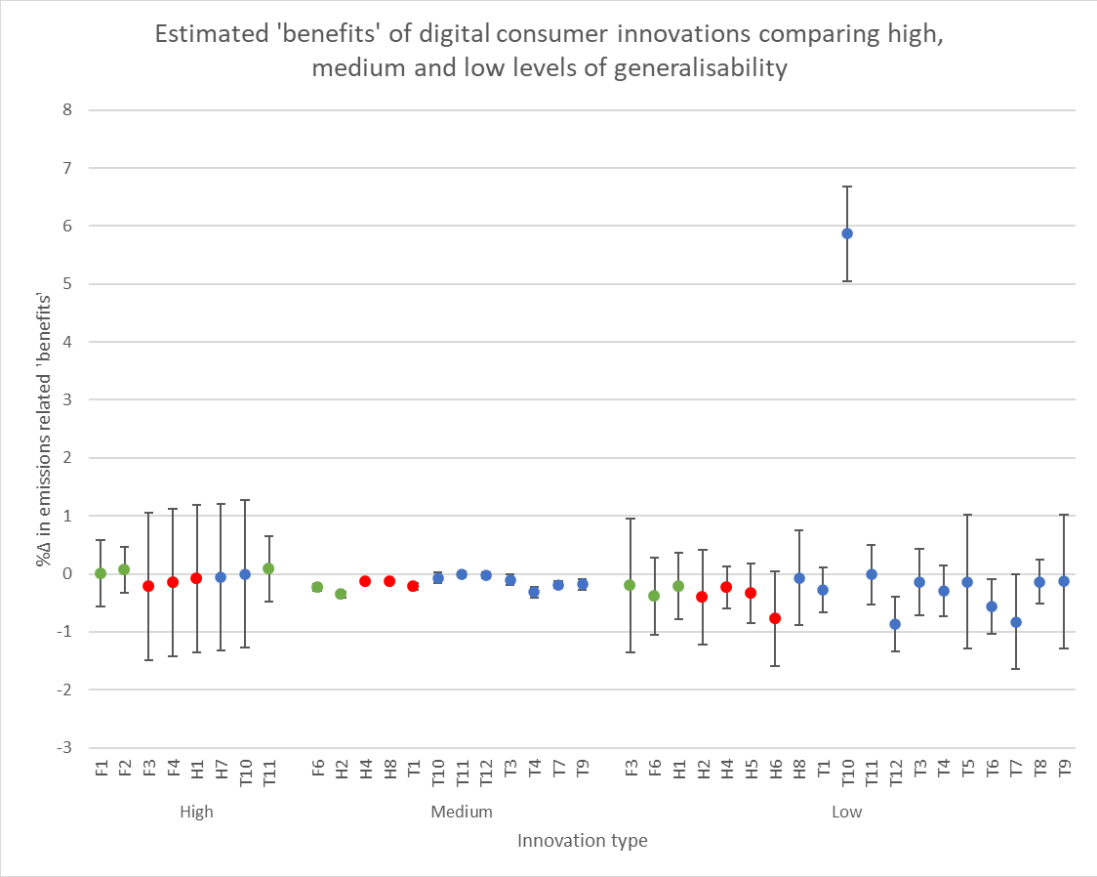


Figure 3 – '*Benefits*' of digital consumer innovations, comparing levels of generalisability

Key Finding: There is some support for H3. Estimated '*benefits*' with low generalisability are larger with moderate to large standard errors. Standard errors are relatively large for the high external validity subset of '*benefits*' estimates. In this respect generalisability relates to aspects of the study design such as the sample size, the nature of the underpinning data (observed or simulated), and the potential for self-selection (opt-in) bias.

H4 Estimated '*benefits*' from changes in activity are larger than estimated changes in energy or carbon emissions

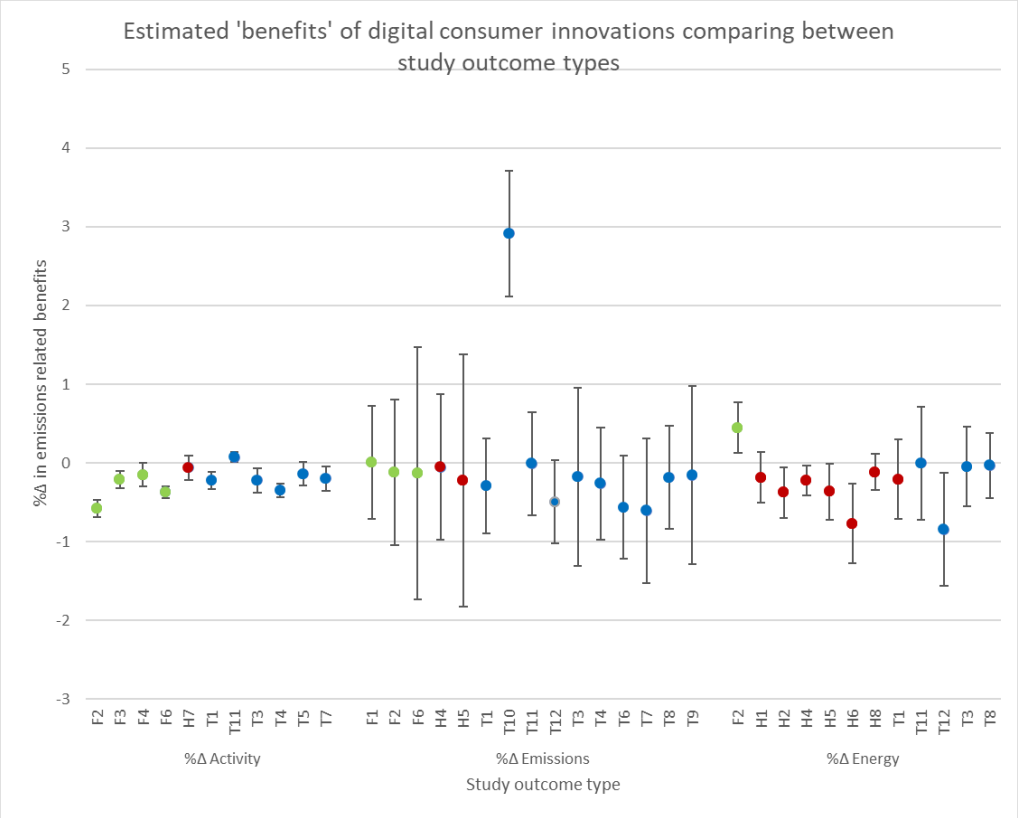


Figure 4 – 'Benefits' of digital consumer innovations, comparing outcome types

Key Finding: There is strong support for H4. Although size of 'benefits' appear similar across the three different metrics of outcome type, estimates of %Δ Activity have less sampling variation and are potentially more generalisable. Sampling variation is also much higher in %Δ emissions compared to %Δenergy. These findings are consistent with the wider literature. Measures of consumer activity associated with digital consumer innovations (and to some extent energy use) is a more direct metric than estimating reduction in CO_2 emissions. Estimates of reductions in CO_2 emissions are several steps removed from activity and energy metrics [8]. There is an additional level of complexity and uncertainty related to estimates of CO_2 emissions [15]. This complexity includes the need for a wider range of assumptions, differing contexts, factors in scaling up, and inclusion of indirect effects.

H5 Estimated '*benefits*' are larger in simulations than in empirically based approaches

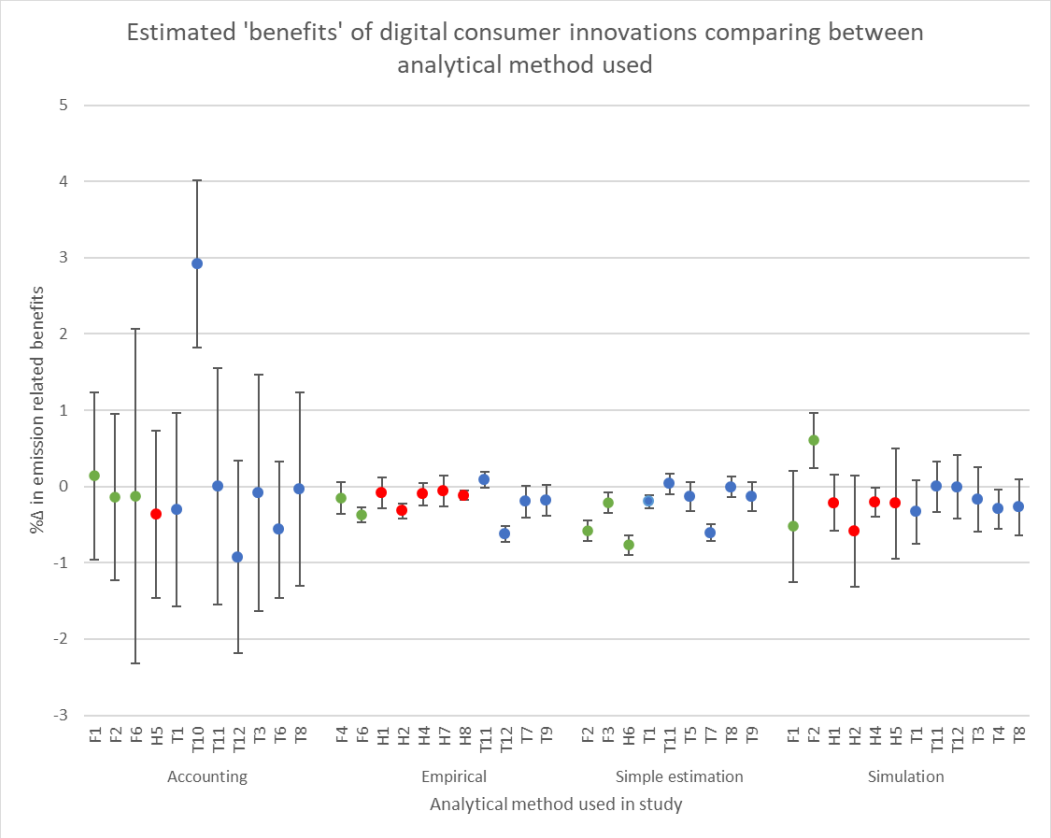


Figure 5 – 'Benefits' of digital consumer innovations, comparing analytical methods

We find some support for H5. There is significant evidence of sampling variability within accounting and simulation methods compared to empirical approaches. These differences in methodological approach that make direct comparisons of effect sizes difficult. Estimations based on observed activity or consumption data in real world conditions are potentially more accurate than those based on simulation models. Simulation models incorporate a wide range of assumptions and involve scenarios representing different levels of adoption.

4. Conclusion and next steps

This report has two main objectives: (1) To identify sources of statistical variation between estimates of the *'benefits'* of digital consumer innovations and (2) To evaluate the extent to which pooling of these estimates could create valid and reliable measures of the '*benefits*' of digital consumer innovations. Consistent with our expectations we do find variation in the size and direction of 'benefits' estimated between innovation types. However, indications are that these are likely to be more reliable as 'pooled' estimates within a meta-analysis framework when they also distinguish between particular aspects of methodological variation between studies, most noticeably differences in how '*benefits*' are measured and in the 'analytical method' used in the study.

Results indicate the need to consider methodological subsets to estimate innovation disaggregated effect sizes. Next steps will involve assessing the suitability of the data for pooled meta-analysis. In the next stage of this work we will perform meta-analysis controlling for a range of study characteristics. Our main aims will be:

- to understand the key drivers of effect size heterogeneity.

- To characterise innovation-specific emission-reduction potentials (contingent on methodological differences).
- To identify sources of unaccounted variability, such as rebound effects. Rebound effects are known to arise from the complex interactions between users, preferences and policy interventions. They are key because any gains in technical efficiency can be offset by increases in use [12, 13].

References

(1) Borenstein, M., Cooper, H., Hedges, L., & Valentine, J. (2009). Effect sizes for continuous data. *The handbook of research synthesis and meta-analysis, 2,* 221-235.

(2) Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, Welch VA (editors). *Cochrane Handbook for Systematic Reviews of Interventions*. 2nd Edition. Chichester (UK): John Wiley & Sons, 2019.

(3) Creutzig, F., J. Roy, P. Devine-Wright, J. Díaz-José, F.W. Geels, A. Grubler, N. Maïzi, E. Masanet, Y. Mulugetta, C.D. Onyige, P.E. Perkins, A. Sanches-Pereira, E.U. Weber, (2022). Demand, services and social aspects of mitigation. In *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.007.

(4) Greening, L. A., Greene, D. L., & Difiglio, C. (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

(5) Kelley, K., & Preacher, K. J. (2012). On effect size. *Psychological methods, 17*(2), 137. https://psycnet.apa.org/doi/10.1037/a0028086

(6) Saunders, H. 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

(7) Sorrell, S. (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

(8) Wilson, C. (2018). Disruptive low-carbon innovations. *Energy Research & Social Science, 37*, 216-223. https://doi.org/10.1016/j.erss.2017.10.053

(9) Wilson, C., Pettifor, H., Cassar, E., Kerr, L., & Wilson, M. (2019). The potential contribution of disruptive low-carbon innovations to 1.5 C climate mitigation. *Energy Efficiency, 12*, 423-440. https://doi.org/10.1007/s12053-018-9679-8

(10) 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. https://doi.org/10.1146/annurev-environ-012320-082424

(11) Agresti, A., & Finlay, B. (2009). Statistical Methods for Social Sciences. Pearson. Prentice Hall.

(12) Coulombel, N., Boutueil, V., Liu, L., Viguie, V., & Yin, B. (2019). Substantial rebound effects in urban ridesharing: Simulating travel decisions in Paris, France. *Transportation Research Part D: Transport and Environment, 71,* 110-126.

(13) Wadud, Z., MacKenzie, D., & Leiby, P. (2016). Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Transportation Research Part A: Policy and Practice, 86*, 1-18.

(14) Khanna, T., Baiocchi, G., Callaghan, M., Creutzig, F., Guias, H. B., Haddaway, N., ... & Minx, J. (2020). Reducing carbon emissions of households through monetary incentives and behavioral interventions: a meta-analysis. *Research Square*. https://doi.org/10.21203/rs.3.rs-124386/v1

(15) Liu, Z., Miwa, T., Zeng, W., & Morikawa, T. (2018). An agent-based simulation model for shared autonomous taxi system. *Asian Transport Studies, 5*(1), 1-13.

Appendix 1 Studies from which estimates of '*benefits*' were derived

1. Adika, C.O., Wang, L. (2014). Smart charging and appliance scheduling approaches to demand side management. *International Journal of Electrical Power & Energy Systems 57*, 232–240.
2. AlFaris, F., Juaidi, A., & Manzano-Agugliaro, F. (2017). Intelligent homes' technologies to optimize the energy performance for the net zero energy home. *Energy and Buildings, 153*, 262-274.
3. Baptista, P., Melo, S., & Rolim, C. (2014). Energy, environmental and mobility impacts of car-sharing systems. Empirical results from Lisbon, Portugal. *Procedia-Social and Behavioral Sciences, 111*, 28-37.
4. Bauer, G. S., Greenblatt, J. B., & Gerke, B. F. (2018). Cost, energy, and environmental impact of automated electric taxi fleets in Manhattan. *Environmental Science & Technology, 52*(8), 4920-4928.
5. Beattie Passive (2017). *Case Study: Retrofit for Social Housing - Solihll, Birmingham* [online]. Beattie Passive, Norwich, UK. https://www.beattiepassive.com/projects/solihull-deep-retrofit-for-social-housing/
6. Beaudin, M & Zareipour, H. (2015). Home energy management systems: A review of modelling and complexity. *Renewable and Sustainable Energy Reviews, 45*, 318–335
7. Blondel, B., Mispelon, C., & Ferguson, J. (2011). *Cycle more often 2 cooldown the Planet! Quantifying CO2 savings of cycling*. European Cyclists's Federation ECF, Brussels, Belgium.
8. Bonilla-Alicea, R. J., Watson, B. C., Shen, Z., Tamayo, L., & Telenko, C. (2020). Life cycle assessment to quantify the impact of technology improvements in bike-sharing systems. *Journal of Industrial Ecology, 24*(1), 138-148.
9. Borggren, C., Moberg, Å., Räsänen, M., & Finnveden, G. (2013). Business meetings at a distance–decreasing greenhouse gas emissions and cumulative energy demand? *Journal of Cleaner Production, 41*, 126-139.
10. Bozchalui, M. C., Hashmi, S. A., Hassen, H., Canizares, C. A., & Bhattacharya, K. (2012). Optimal operation of residential energy hubs in smart grids. *IEEE Transactions on Smart Grid, 3*(4), 1755-1766.
11. Bruck, B. P., Incerti, V., Iori, M., & Vignoli, M. (2017). Minimizing CO2 emissions in a practical daily carpooling problem. *Computers & Operations Research, 81*, 40-50.
12. Brunner, H., & Hirz, M. (2014). *The Potential of New Vehicle Concepts for Transport Optimization and GHG Emission Reduction in Urban Areas* (No. 2014-01-1005). SAE Technical Paper.
13. Bullock, C., Brereton, F., & Bailey, S. (2017). The economic contribution of public bike-share to the sustainability and efficient functioning of cities. *Sustainable cities and society, 28*, 76-87.
14. Byun, J., Hong, I., Lee, B., Park, S. (2013). Intelligent household LED lighting system considering energy efficiency and user satisfaction. *IEEE Transactions on Consumer Electronics, 59*, 70–76.
15. Cai, H., Wang, X., Adriaens, P., & Xu, M. (2019). Environmental benefits of taxi ride sharing in Beijing. *Energy, 174*, 503-508.
16. Cairns, S., Behrendt, F., Raffo, D., Beaumont, C., & Kiefer, C. (2017). Electrically-assisted bikes: Potential impacts on travel behaviour. *Transportation research part A: policy and practice, 103*, 327-342.
17. Chakrabarti, S. (2018). Does telecommuting promote sustainable travel and physical activity? *Journal of Transport & Health, 9*, 19-33.
18. Chakravarty, P., & Gupta, A. (2013). Impact of energy disaggregation on consumer behavior., in Behavior, *Energy and Climate Change Conference (BECC). UC Berkeley, Sacramento CA, 19th Nov. 2013*.
19. Chen, Y., Gonder, J., Young, S., & Wood, E. (2019). Quantifying autonomous vehicles national fuel consumption impacts: A data-rich approach. *Transportation Research Part A: Policy and Practice, 122,* 134-145.
20. Chen, Y., Young, S., Qi, X., & Gonder, J. (2015, October). Estimate of fuel consumption and GHG emission impact from an automated mobility district. In *2015 International Conference on Connected Vehicles and Expo (ICCVE)* (pp. 271-278). IEEE.
21. Cheng, J. (2018). *Potential for taxi ridesharing in New York City*. [Doctoral dissertation, University of California, Irvine], 48 pp.
22. Chew, I., Karunatilaka, D., Tan, C.P., Kalavally, V. (2017). Smart lighting: The way forward? Reviewing the past to shape the future. *Energy and Buildings, 149*, 180–191.

23. Choo, S., Mokhtarian, P. L., & Salomon, I. (2005). Does telecommuting reduce vehicle-miles traveled? An aggregate time series analysis for the US. *Transportation, 32*, 37-64.
24. Clewlow, R. R. (2016). Carsharing and sustainable travel behavior: Results from the San Francisco Bay Area. *Transport Policy, 51*, 158-164.
25. Coroama, V. C., Hilty, L. M., & Birtel, M. (2012). Effects of Internet-based multiple-site conferences on greenhouse gas emissions. *Telematics and Informatics, 29*(4), 362-374.
26. Coulombel, N., Boutueil, V., Liu, L., Viguie, V., & Yin, B. (2019). Substantial rebound effects in urban ridesharing: Simulating travel decisions in Paris, France. *Transportation Research Part D: Transport and Environment, 71,* 110-126.
27. de Abreu e Silva, J. D. A., & Melo, P. C. (2018). Does home-based telework reduce household total travel? A path analysis using single and two worker British households. *Journal of Transport Geography, 73,* 148-162.
28. Ehrhardt-Martinez, K., Donnelly, K. A., & Laitner, S. (2010, June). *Advanced metering initiatives and residential feedback programs: a meta-review for household electricity-saving opportunities*. Report Number E105. Washington, DC: American Council for an Energy-Efficient Economy (ACEEE).
29. Energiesprong (2015). *Transition Zero*. http://transition-zero.eu/wp-content/uploads/2016/09/EnergieSprong_UK-Transition_Zero_document.pdf
30. Erdmann, L. & Hilty, L. M. (2010). Scenario analysis: exploring the macroeconomic impacts of information and communication technologies on greenhouse gas emissions. *Journal of Industrial Ecology, 14*(5) 826-843.
31. Farr-Wharton, G., Foth, M., & Choi, J. H. J. (2012, November). Colour coding the fridge to reduce food waste. In *Proceedings of the 24th Australian Computer-Human Interaction Conference* (pp. 119-122).
32. Fenton, K.L. (2017). *Unpacking the sustainability of Meal Kit Delivery: a comparative analysis of energy use, carbon emissions, and related costs for Meal Kit services and grocery stores*. [MSc Dissertation, The University of Texas at Austin].
33. Fernández, R. Á. (2018). A more realistic approach to electric vehicle contribution to greenhouse gas emissions in the city. *Journal of Cleaner Production, 172*, 949-959.
34. Firnkorn, J., & Müller, M. (2011). What will be the environmental effects of new free-floating car-sharing systems? The case of car2go in Ulm. *Ecological economics, 70*(8), 1519-1528.
35. Fremstad, A. (2017) Does Craigslist Reduce Waste? Evidence from California and Flordia. Ecological Economics 132, 135-143.
36. Fulton, L., Mason, J., & Meroux, D. (2017). *Three revolutions in urban transportation: how to achieve the full potential of vehicle electrification, automation, and shared mobility in urban transportation systems around the world by 2050* (No. STEPS-2050).
37. Gawron, J. H., Keoleian, G. A., De Kleine, R. D., Wallington, T. J., & Kim, H. C. (2018). Life cycle assessment of connected and automated vehicles: sensing and computing subsystem and vehicle level effects. *Environmental science & technology, 52*(5), 3249-3256.
38. Gee, I. M., Davidson, F. T., Speetles, B. L., & Webber, M. E. (2019). Deliver Me from food waste: Model framework for comparing the energy use of meal-kit delivery and groceries. *Journal of Cleaner Production, 236*, 117587.
39. Guerin, T.F. (2017). A demonstration of how virtual meetings can enhance sustainability in a corporate context: Quantified benefits of virtual meetings through video conferencing. *Environmental Quality Management, 27*(1), 75-81.
40. Hall, M. (2016) Five MPs volunteer to trial new Sainsbury's food waste app. *Businesswaste*. https://www.about.sainsburys.co.uk/~/media/Files/S/Sainsburys/WLSM_FINAL_REPORT.pdf
41. Heard, B. R., Bandekar, M., Vassar, B., & Miller, S. A. (2019). Comparison of life cycle environmental impacts from meal kits and grocery store meals. *Resources, Conservation and Recycling, 147*, 189-200. https://doi.org/10.1016/j.resconrec.2019.04.008.
42. Hiselius, L. W., & Svensson, Å. (2017). E-bike use in Sweden–CO_2 effects due to modal change and municipal promotion strategies. *Journal of cleaner production, 141*, 818-824.
43. Holmner, Å., Ebi, K. L., Lazuardi, L., & Nilsson, M. (2014). Carbon footprint of telemedicine solutions-unexplored opportunity for reducing carbon emissions in the health sector. *PloS one, 9*(9), e105040.

44. Houston, K., & Reay, D. S. (2011). The impact of information and communication technology on GHG emissions: how green are virtual worlds? *Carbon Management, 2*(6), 629-643.
45. Ilic, M., Black, J. W., & Watz, J. L. (2002, January). Potential benefits of implementing load control. In *2002 IEEE Power Engineering Society Winter Meeting. Conference Proceedings* (Cat. No. 02CH37309) (Vol. 1, pp. 177-182). IEEE.
46. Isley, S. C., Ketcham, R., & Arent, D. J. (2017). Using augmented reality to inform consumer choice and lower carbon footprints. *Environmental Research Letters, 12*(6), 064002.
47. ITF (2017a). *Shared Mobility: Simulations for Auckland*. Paris, France: International Transport Forum (ITF), OECD
48. ITF (2017b). *Transition to Shared Mobility: How large cities can deliver inclusive transport services.* Paris, France*:* International Transport Forum (ITF), OECD.
49. Jacobson, S. H., & King, D. M. (2009). Fuel saving and ridesharing in the US: Motivations, limitations, and opportunities. *Transportation Research Part D: Transport and Environment, 14*(1), 14-21.
50. Jenkins, D. P., Tucker, R., & Rawlings, R. (2009). Modelling the carbon-saving performance of domestic ground-source heat pumps. *Energy and Buildings, 41*(6), 587-595.
51. Ji, S., Cherry, C. R., J. Bechle, M., Wu, Y., & Marshall, J. D. (2012). Electric vehicles in China: emissions and health impacts. *Environmental Science & Technology, 46*(4), 2018-2024.
52. Jin, X., Baker, K., Christensen, D., & Isley, S. (2017). Foresee: A user-centric home energy management system for energy efficiency and demand response. *Applied Energy, 205*, 1583-1595.
53. Karlsson, M., Sochor, J., Aapaoja, A., Eckhardt, J., & König, D. (2017). Deliverable 4-Impact Assessment: MAASiFiE project funded by CEDR*. Conference of European Directors of Roads (CEDR*).
54. Khajenasiri, I., Estebsari, A., Verhelst, M., Gielen, G. (2017). A Review on Internet of Things Solutions for Intelligent Energy Control in Buildings for Smart City Applications. *Energy Procedia, 111*, 770–779.
55. Koh, H. (2016). A new app to save food at the 11th Hour. *Eco-business* [online], 15 November 2016. https://www.eco-business.com/news/a-new-app-to-save-food-at-the-11th-hour/
56. Laidi, R., Djenouri, D., Ringel, M. (2019). Commercial Technologies for Advanced Light Control in Smart Building Energy Management Systems: A Comparative Study. *Energy and Power Engineering 11*: 283-302.
57. Li, N., Chen, L., & Low, S. H. (2011, July). Optimal demand response based on utility maximization in power networks. In *2011 IEEE power and energy society general meeting* (pp. 1-8). IEEE.
58. Lister, K., & Harnish, T. (2011). The shifting nature of work in the UK: Bottom line benefits of telework. *Telework Research Network* (sponsored by Citrix Online), Global Workplace Analytics, Carlsbad, California, U.S. 18 pp.
59. Liu, Z., Miwa, T., Zeng, W., & Morikawa, T. (2018). An agent-based simulation model for shared autonomous taxi system. *Asian Transport Studies, 5*(1), 1-13.
60. Lokhandwala, M., & Cai, H. (2018). Dynamic ride sharing using traditional taxis and shared autonomous taxis: A case study of NYC. *Transportation Research Part C: Emerging Technologies, 97,* 45-60.
61. Louis, J. N., Caló, A., & Pongrácz, E. (2014). Smart houses for energy efficiency and carbon dioxide emission reduction. *Energy*, 44-50.
62. Martin, E., & Shaheen, S. (2016). Impacts of car2go on vehicle ownership, modal shift, vehicle miles traveled, and greenhouse gas emissions: An analysis of five North American cities. *Transportation Sustainability Research Center, UC Berkeley, 3*.
63. McCalley, L. T., & Midden, C. J. (2002). Energy conservation through product-integrated feedback: The roles of goal-setting and social orientation. *Journal of Economic Psychology, 23*(5), 589-603.
64. Merlin, L. A. (2017). Comparing automated shared taxis and conventional bus transit for a small city. *Journal of Public Transportation, 20*(2), 19-39.
65. Minett, P., & Pearce, J. (2011). Estimating the energy consumption impact of casual carpooling. *Energies, 4*(1), 126-139.
66. Moro, A., & Lonza, L. (2018). Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. *Transportation Research Part D: Transport and Environment, 64,* 5-14.
67. Namazu, M., & Dowlatabadi, H. (2015). Characterizing the GHG emission impacts of carsharing: a case of Vancouver. *Environmental Research Letters, 10*(12), 124017.

68. Nijland, H., & van Meerkerk, J. (2017). Mobility and environmental impacts of car sharing in the Netherlands. *Environmental Innovation and Societal Transitions, 23*, 84-91.
69. Nilsson, A., Lazarevic, D., Brandt, N., & Kordas, O. (2018). Household responsiveness to residential demand response strategies: Results and policy implications from a Swedish field study. *Energy policy, 122*, 273-286.
70. Nordelöf, A., Messagie, M., Tillman, A. M., Ljunggren Söderman, M., & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment, 19,* 1866-1890.
71. Ong, D., Moors, T., & Sivaraman, V. (2014). Comparison of the energy, carbon and time costs of videoconferencing and in-person meetings. *Computer Communications, 50,* 86-94.
72. Ota, M., Vo, H., Silva, C., & Freire, J. (2016). Stars: Simulating taxi ride sharing at scale. *IEEE Transactions on Big Data, 3*(3), 349-361.
73. Paatero, J. V., & Lund, P. D. (2006). A model for generating household electricity load profiles. *International Journal of Energy Research, 30*(5), 273-290.
74. Park, T et al (2017). *Evaluating the Nest Learning Thermostat: Four field experiments evaluating the energy saving potential of Nest's Smart Heating Control*. A report by the Behavioural Insights Team. London. (31 October 2017).
75. Peano, C., Tecco, N., & Girgenti, V. (2018). Applied Environmental Sustainability of Fruit and Vegetables in Different Distribution Channels (AFNs and Large-Scale Retail). In, Corsi, A., Barbera, F., Dansero, E., & Peano, C. (Eds.). *Alternative Food Networks: An Interdisciplinary Assessment*, 251-272. Alternative Food Networks. McMillan, London.
76. Pérez-Neira, D., & Grollmus-Venegas, A. (2018). Life-cycle energy assessment and carbon footprint of peri-urban horticulture. A comparative case study of local food systems in Spain. *Landscape and Urban Planning, 172,* 60-68.
77. Peters, A. (2016). Cooking with a meal kit may waste 62% less food than grocery store ingredients. *Fast Company* [online], 19 September 2016
78. Phiri, G., & Trevorrow, P. (2019, June). Sustainable Household Food Management Using Smart Technology. In *2019 10th International Conference on Dependable Systems, Services and Technologies (DESSERT)* (pp. 112-119). IEEE.
79. Rabbitt, N., & Ghosh, B. (2013). A study of feasibility and potential benefits of organised car sharing in Ireland. *Transportation Research Part D: Transport and Environment, 25*, 49-58.
80. Ringel, M., Laidi, R., Djenouri, D. (2019). Multiple Benefits through Smart Home Energy Management Solutions — A Simulation-Based Case. *Energies, 12*, 1537
81. Roth, K. W., Rhodes, T., & Ponoum, R. (2008, May). The energy and greenhouse gas emission impacts of telecommuting in the US. In *2008 IEEE International Symposium on Electronics and the Environmen*t (pp. 1-6). IEEE.
82. Seimbab W. Magarian D (2013). Zero Emission Local Use Vehicles: The Neglected Sustainable Transportation Mode. *Neighborhood Electric Vehicle Demonstration Project Final Report June 30, 2013*. South Bay Cities Council of Governments. Torrance, California, USA. 184pp.
83. Shabanpour, R., Golshani, N., Tayarani, M., Auld, J., & Mohammadian, A. K. (2018). Analysis of telecommuting behaviour and impacts on travel demand and the environment. *Transportation Research Part D: Transport and Environment*, 62, 563-576.
84. Shaw, J., Kor, A. L., & Pattinson, C. (2016, August). An Evaluation of the Impact of Remote Collaboration Tools on Corporate Sustainability. In *2016 IEEE 14th Intl Conf on Dependable, Autonomic and Secure Computing, 14th Intl Conf on Pervasive Intelligence and Computing, 2nd Intl Conf on Big Data Intelligence and Computing and Cyber Science and Technology Congress (DASC/PiCom/DataCom/CyberSciTech)* (pp. 257-262). IEEE.
85. Siikavirta, H., Punakivi, M., Kärkkäinen, M., & Linnanen, L. (2002). Effects of e-commerce on greenhouse gas emissions: a case study of grocery home delivery in Finland. *Journal of industrial ecology, 6*(2), 83-97.
86. Sivasakthivel, T., Murugesan, K., & Sahoo, P. K. (2014). A study on energy and CO_2 saving potential of ground source heat pump system in India. *Renewable and Sustainable Energy Reviews, 32*, 278-293.
87. Sokoloski, R. (2015). *Disaggregated electricity consumption: using appliance-specific feedback to promote energy conservation*. M.A. California State University San Marcos, 2nd Jul. 2015.

88. Spagnolli, A., Corradi, N., Gamberini, L., Hoggan, E., Jacucci, G., Katzeff, C., ... & Jonsson, L. (2011). Eco-feedback on the go: Motivating energy awareness. *Computer, 44*(5), 38-45.
89. Tiefenbeck, V., Wörner, A., Schöb, S., Fleisch, E., & Staake, T. (2019). Real-time feedback promotes energy conservation in the absence of volunteer selection bias and monetary incentives. *Nature Energy, 4*(1), 35-41.
90. Ueno, T., Sano, F., Saeki, O., & Tsuji, K. (2006). Effectiveness of an energy-consumption information system on energy savings in residential houses based on monitored data. *Applied Energy, 83*(2), 166-183.
91. Wadud, Z., MacKenzie, D., & Leiby, P. (2016). Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Transportation Research Part A: Policy and Practice, 86*, 1-18..
92. Wilson, C., Pettifor, H., Cassar, E., Kerr, L., & Wilson, M. (2019). The potential contribution of disruptive low-carbon innovations to 1.5 C climate mitigation. *Energy Efficiency, 12*, 423-440.
93. Wong, K. (2016). A Dutch App Aims to Save Millions in Food Waste. *Seeker* [online], 27 December 2016. https://www.seeker.com/a-dutch-app-aims-to-save-millions-in-food-waste-2166906531.html
94. Woolley, E., Garcia-Garcia, G., Tseng, R., & Rahimifard, S. (2016). Manufacturing resilience via inventory management for domestic food waste. *Procedia CIRP, 40*, 372-377.
95. Wrap (2014). *The impact of Love Food Hate Waste*. Waste and Resources Action Programme [online], https://wrap.org.uk/
96. Yu, B., Ma, Y., Xue, M., Tang, B., Wang, B., Yan, J., & Wei, Y. M. (2017). Environmental benefits from ridesharing: A case of Beijing. *Applied energy, 191*, 141-152.
97. Yuan, S., Stainsby, W., Li, M., Xu, K., Waite, M., Zimmerle, D., ... & Modi, V. (2019). Future energy scenarios with distributed technology options for residential city blocks in three climate regions of the United States. *Applied Energy, 237*, 60-69.
98. Zhang, Y., & Mi, Z. (2018). Environmental benefits of bike sharing: A big data-based analysis. *Applied energy, 220*, 296-301.

Appendix 2 – List of Studies, grouped by domain type and innovation type

Table x - Studies of digital consumer innovations in the transport domain

T1	Baptista, P., Melo, S., & Rolim, C. (2014). Energy, environmental and mobility impacts of car-sharing systems. Empirical results from Lisbon, Portugal. *Procedia-Social and Behavioral Sciences, 111*, 28-37.
T1	Clewlow, R. R. (2016). Carsharing and sustainable travel behavior: Results from the San Francisco Bay Area. *Transport Policy, 51*, 158-164.
T1	Firnkorn, J., & Müller, M. (2011). What will be the environmental effects of new free-floating car-sharing systems? The case of car2go in Ulm. *Ecological economics, 70*(8), 1519-1528.
T1	Martin, E., & Shaheen, S. (2016). Impacts of car2go on vehicle ownership, modal shift, vehicle miles traveled, and greenhouse gas emissions: An analysis of five North American cities. *Transportation Sustainability Research Center, UC Berkeley, 3*.
T1	Namazu, M., & Dowlatabadi, H. (2015). Characterizing the GHG emission impacts of carsharing: a case of Vancouver. *Environmental Research Letters, 10*(12), 124017.
T1	Nijland, H., & van Meerkerk, J. (2017). Mobility and environmental impacts of car sharing in the Netherlands. *Environmental Innovation and Societal Transitions, 23*, 84-91.
T1	Rabbitt, N., & Ghosh, B. (2013). A study of feasibility and potential benefits of organised car sharing in Ireland. *Transportation Research Part D: Transport and Environment, 25*, 49-58.
T3	Bruck, B. P., Incerti, V., Iori, M., & Vignoli, M. (2017). Minimizing CO2 emissions in a practical daily carpooling problem. *Computers & Operations Research, 81*, 40-50.
T3	Coulombel, N., Boutueil, V., Liu, L., Viguie, V., & Yin, B. (2019). Substantial rebound effects in urban ridesharing: Simulating travel decisions in Paris, France. *Transportation Research Part D: Transport and Environment, 71,* 110-126.
T3	Jacobson, S. H., & King, D. M. (2009). Fuel saving and ridesharing in the US: Motivations, limitations, and opportunities. *Transportation Research Part D: Transport and Environment, 14*(1), 14-21.

T3	Minett, P., & Pearce, J. (2011). Estimating the energy consumption impact of casual carpooling. *Energies, 4*(1), 126-139.
T3	Yu, B., Ma, Y., Xue, M., Tang, B., Wang, B., Yan, J., & Wei, Y. M. (2017). Environmental benefits from ridesharing: A case of Beijing. *Applied energy, 191*, 141-152.
T4	Cai, H., Wang, X., Adriaens, P., & Xu, M. (2019). Environmental benefits of taxi ride sharing in Beijing. *Energy, 174*, 503-508.
T4	Cheng, J. (2018). *Potential for taxi ridesharing in New York City*. [Doctoral dissertation, University of California, Irvine], 48 pp.
T4	ITF (2017a). *Shared Mobility: Simulations for Auckland*. Paris, France: International Transport Forum (ITF), OECD
T4	ITF (2017b). *Transition to Shared Mobility: How large cities can deliver inclusive transport services.* Paris, France*:* International Transport Forum (ITF), OECD.
T4	Liu, Z., Miwa, T., Zeng, W., & Morikawa, T. (2018). An agent-based simulation model for shared autonomous taxi system. *Asian Transport Studies, 5*(1), 1-13.
T4	Lokhandwala, M., & Cai, H. (2018). Dynamic ride sharing using traditional taxis and shared autonomous taxis: A case study of NYC. *Transportation Research Part C: Emerging Technologies, 97,* 45-60.
T4	Merlin, L. A. (2017). Comparing automated shared taxis and conventional bus transit for a small city. *Journal of Public Transportation, 20*(2), 19-39.
T4	Ota, M., Vo, H., Silva, C., & Freire, J. (2016). Stars: Simulating taxi ride sharing at scale. *IEEE Transactions on Big Data, 3*(3), 349-361.
T5	Karlsson, M., Sochor, J., Aapaoja, A., Eckhardt, J., & König, D. (2017). Deliverable 4-Impact Assessment: MAASiFiE project funded by CEDR. *Conference of European Directors of Roads (CEDR*).
T6	Fernández, R. Á. (2018). A more realistic approach to electric vehicle contribution to greenhouse gas emissions in the city. *Journal of Cleaner Production, 172*, 949-959.
T6	Moro, A., & Lonza, L. (2018). Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. *Transportation Research Part D: Transport and Environment, 64,* 5-14.
T6	Nordelöf, A., Messagie, M., Tillman, A. M., Ljunggren Söderman, M., & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment, 19,* 1866-1890.
T7	Blondel, B., Mispelon, C., & Ferguson, J. (2011). *Cycle more often 2 cooldown the Planet! Quantifying CO2 savings of cycling*. European Cyclists's Federation ECF, Brussels, Belgium.
T7	Cairns, S., Behrendt, F., Raffo, D., Beaumont, C., & Kiefer, C. (2017). Electrically-assisted bikes: Potential impacts on travel behaviour. *Transportation research part A: policy and practice, 103*, 327-342.
T7	Hiselius, L. W., & Svensson, Å. (2017). E-bike use in Sweden–CO_2 effects due to modal change and municipal promotion strategies. *Journal of cleaner production, 141*, 818-824.
T7	Ji, S., Cherry, C. R., J. Bechle, M., Wu, Y., & Marshall, J. D. (2012). Electric vehicles in China: emissions and health impacts. *Environmental Science & Technology, 46*(4), 2018-2024.
T8	Bauer, G. S., Greenblatt, J. B., & Gerke, B. F. (2018). Cost, energy, and environmental impact of automated electric taxi fleets in Manhattan. *Environmental Science & Technology, 52*(8), 4920-4928.
T8	Chen, Y., Gonder, J., Young, S., & Wood, E. (2019). Quantifying autonomous vehicles national fuel consumption impacts: A data-rich approach. *Transportation Research Part A: Policy and Practice, 122,* 134-145.
T8	Chen, Y., Young, S., Qi, X., & Gonder, J. (2015, October). Estimate of fuel consumption and GHG emission impact from an automated mobility district. In *2015 International Conference on Connected Vehicles and Expo (ICCVE)* (pp. 271-278). IEEE.
T8	Fulton, L., Mason, J., & Meroux, D. (2017). *Three revolutions in urban transportation: how to achieve the full potential of vehicle electrification, automation, and shared mobility in urban transportation systems around the world by 2050* (No. STEPS-2050).
T8	Gawron, J. H., Keoleian, G. A., De Kleine, R. D., Wallington, T. J., & Kim, H. C. (2018). Life cycle assessment of connected and automated vehicles: sensing and computing subsystem and vehicle level effects. *Environmental science & technology, 52*(5), 3249-3256.

T8	Wadud, Z., MacKenzie, D., & Leiby, P. (2016). Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Transportation Research Part A: Policy and Practice, 86*, 1-18.
T9	Brunner, H., & Hirz, M. (2014). *The Potential of New Vehicle Concepts for Transport Optimization and GHG Emission Reduction in Urban Areas* (No. 2014-01-1005). SAE Technical Paper.
T9	Seimbab W. Magarian D (2013). Zero Emission Local Use Vehicles: The Neglected Sustainable Transportation Mode. *Neighborhood Electric Vehicle Demonstration Project Final Report June 30, 2013*. South Bay Cities Council of Governments. Torrance, California, USA. 184pp.
T10	Bonilla-Alicea, R. J., Watson, B. C., Shen, Z., Tamayo, L., & Telenko, C. (2020). Life cycle assessment to quantify the impact of technology improvements in bike-sharing systems. *Journal of Industrial Ecology, 24*(1), 138-148.
T10	Bullock, C., Brereton, F., & Bailey, S. (2017). The economic contribution of public bike-share to the sustainability and efficient functioning of cities. *Sustainable cities and society, 28*, 76-87.
T10	Zhang, Y., & Mi, Z. (2018). Environmental benefits of bike sharing: A big data-based analysis. *Applied energy, 220*, 296-301.
T11	Chakrabarti, S. (2018). Does telecommuting promote sustainable travel and physical activity? *Journal of Transport & Health, 9*, 19-33.
T11	Choo, S., Mokhtarian, P. L., & Salomon, I. (2005). Does telecommuting reduce vehicle-miles traveled? An aggregate time series analysis for the US. *Transportation, 32*, 37-64.
T11	de Abreu e Silva, J. D. A., & Melo, P. C. (2018). Does home-based telework reduce household total travel? A path analysis using single and two worker British households. *Journal of Transport Geography, 73,* 148-162.
T11	Erdmann, L., & Hilty, L. M. (2010). Scenario analysis: exploring the macroeconomic impacts of information and communication technologies on greenhouse gas emissions. *Journal of Industrial Ecology, 14*(5), 826-843.
T11	Lister, K., & Harnish, T. (2011). The shifting nature of work in the UK: Bottom line benefits of telework. *Telework Research Network* (sponsored by Citrix Online), Global Workplace Analytics, Carlsbad, California, U.S. 18 pp.
T11	Roth, K. W., Rhodes, T., & Ponoum, R. (2008, May). The energy and greenhouse gas emission impacts of telecommuting in the US. In *2008 IEEE International Symposium on Electronics and the Environmen*t (pp. 1-6). IEEE.
T11	Shabanpour, R., Golshani, N., Tayarani, M., Auld, J., & Mohammadian, A. K. (2018). Analysis of telecommuting behaviour and impacts on travel demand and the environment. *Transportation Research Part D: Transport and Environment*, 62, 563-576.
T12	Borggren, C., Moberg, Å., Räsänen, M., & Finnveden, G. (2013). Business meetings at a distance–decreasing greenhouse gas emissions and cumulative energy demand? *Journal of Cleaner Production, 41*, 126-139.
T12	Coroama, V. C., Hilty, L. M., & Birtel, M. (2012). Effects of Internet-based multiple-site conferences on greenhouse gas emissions. *Telematics and Informatics, 29*(4), 362-374.
T12	Erdmann, L., & Hilty, L. M. (2010). Scenario analysis: exploring the macroeconomic impacts of information and communication technologies on greenhouse gas emissions. *Journal of Industrial Ecology, 14*(5), 826-843.
T12	Guerin, T.F. (2017). A demonstration of how virtual meetings can enhance sustainability in a corporate context: Quantified benefits of virtual meetings through video conferencing. *Environmental Quality Management, 27*(1), 75-81.
T12	Holmner, Å., Ebi, K. L., Lazuardi, L., & Nilsson, M. (2014). Carbon footprint of telemedicine solutions-unexplored opportunity for reducing carbon emissions in the health sector. *PloS one, 9*(9), e105040.
T12	Houston, K., & Reay, D. S. (2011). The impact of information and communication technology on GHG emissions: how green are virtual worlds? *Carbon Management, 2*(6), 629-643.
T12	Ong, D., Moors, T., & Sivaraman, V. (2014). Comparison of the energy, carbon and time costs of videoconferencing and in-person meetings. *Computer Communications, 50,* 86-94.
T12	Shaw, J., Kor, A. L., & Pattinson, C. (2016, August). An Evaluation of the Impact of Remote Collaboration Tools on Corporate Sustainability. In *2016 IEEE 14th Intl Conf on Dependable, Autonomic and Secure Computing, 14th Intl Conf on Pervasive Intelligence and Computing, 2nd Intl Conf on Big Data Intelligence and Computing and Cyber Science and Technology Congress (DASC/PiCom/DataCom/CyberSciTech)* (pp. 257-262). IEEE.

Table Y - Studies of digital consumer innovations in the food domain

F1	Peano, C., Tecco, N., & Girgenti, V. (2018). Applied Environmental Sustainability of Fruit and Vegetables in Different Distribution Channels (AFNs and Large-Scale Retail). In, Corsi, A., Barbera, F., Dansero, E., & Peano, C. (Eds.). *Alternative Food Networks: An Interdisciplinary Assessment*, 251-272. Alternative Food Networks. McMillan, London.
F1	Pérez-Neira, D., & Grollmus-Venegas, A. (2018). Life-cycle energy assessment and carbon footprint of peri-urban horticulture. A comparative case study of local food systems in Spain. *Landscape and Urban Planning, 172,* 60-68.
F1	Siikavirta, H., Punakivi, M., Kärkkäinen, M., & Linnanen, L. (2002). Effects of e-commerce on greenhouse gas emissions: a case study of grocery home delivery in Finland. *Journal of industrial ecology, 6*(2), 83-97.
F2	Fenton, K.L. (2017). *Unpacking the sustainability of Meal Kit Delivery: a comparative analysis of energy use, carbon emissions, and related costs for Meal Kit services and grocery stores*. [MSc Dissertation, The University of Texas at Austin].
F2	Gee, I. M., Davidson, F. T., Speetles, B. L., & Webber, M. E. (2019). Deliver Me from food waste: Model framework for comparing the energy use of meal-kit delivery and groceries. *Journal of Cleaner Production, 236*, 117587.
F2	Heard, B. R., Bandekar, M., Vassar, B., & Miller, S. A. (2019). Comparison of life cycle environmental impacts from meal kits and grocery store meals. *Resources, Conservation and Recycling, 147*, 189-200. https://doi.org/10.1016/j.resconrec.2019.04.008.
F2	Peters, A. (2016). Cooking with a meal kit may waste 62% less food than grocery store ingredients. *Fast Company* [online], 19 September 2016
F3	Koh, H. (2016). A new app to save food at the 11th Hour. *Eco-business* [online], 15 November 2016. https://www.eco-business.com/news/a-new-app-to-save-food-at-the-11th-hour/
F3	Wong, K. (2016). A Dutch App Aims to Save Millions in Food Waste. *Seeker* [online], 27 December 2016. https://www.seeker.com/a-dutch-app-aims-to-save-millions-in-food-waste-2166906531.html
F4	Wrap (2014). *The impact of Love Food Hate Waste*. Waste and Resources Action Programme [online], https://wrap.org.uk/
F6	Farr-Wharton, G., Foth, M., & Choi, J. H. J. (2012, November). Colour coding the fridge to reduce food waste. In *Proceedings of the 24th Australian Computer-Human Interaction Conference* (pp. 119-122).
F6	Hall, M. (2016) Five MPs volunteer to trial new Sainsbury's food waste app. *Businesswaste*. https://www.about.sainsburys.co.uk/~/media/Files/S/Sainsburys/WLSM_FINAL_REPORT.pdf
F6	Isley, S. C., Ketcham, R., & Arent, D. J. (2017). Using augmented reality to inform consumer choice and lower carbon footprints. *Environmental Research Letters, 12*(6), 064002.
F6	Phiri, G., & Trevorrow, P. (2019, June). Sustainable Household Food Management Using Smart Technology. In *2019 10th International Conference on Dependable Systems, Services and Technologies (DESSERT)* (pp. 112-119). IEEE.
F6	Woolley, E., Garcia-Garcia, G., Tseng, R., & Rahimifard, S. (2016). Manufacturing resilience via inventory management for domestic food waste. *Procedia CIRP, 40*, 372-377.

Table X - Studies of digital consumer innovations in the homes domain

H1	Khajenasiri, I., Estebsari, A., Verhelst, M., Gielen, G. (2017). A Review on Internet of Things Solutions for Intelligent Energy Control in Buildings for Smart City Applications. *Energy Procedia, 111*, 770–779.
H1	Park, T et al (2017). *Evaluating the Nest Learning Thermostat: Four field experiments evaluating the energy saving potential of Nest's Smart Heating Control*. A report by the Behavioural Insights Team. London. (31 October 2017).
H1	Ringel, M., Laidi, R., Djenouri, D. (2019). Multiple Benefits through Smart Home Energy Management Solutions — A Simulation-Based Case. *Energies, 12*, 1537
H2	Byun, J., Hong, I., Lee, B., Park, S. (2013). Intelligent household LED lighting system considering energy efficiency and user satisfaction. *IEEE Transactions on Consumer Electronics, 59*, 70–76.
H2	Chew, I., Karunatilaka, D., Tan, C.P., Kalavally, V. (2017). Smart lighting: The way forward? Reviewing the past to shape the future. *Energy and Buildings, 149*, 180–191.
H2	Laidi, R., Djenouri, D., Ringel, M. (2019). Commercial Technologies for Advanced Light Control in Smart Building Energy Management Systems: A Comparative Study. *Energy and Power Engineering 11*: 283-302.
H3	Wilson, C., Pettifor, H., Cassar, E., Kerr, L., & Wilson, M. (2019). The potential contribution of disruptive low-carbon innovations to 1.5 C climate mitigation. *Energy Efficiency, 12*, 423-440.
H4	Adika, C.O., Wang, L. (2014). Smart charging and appliance scheduling approaches to demand side management. *International Journal of Electrical Power & Energy Systems 57*, 232–240.
H4	AlFaris, F., Juaidi, A., & Manzano-Agugliaro, F. (2017). Intelligent homes' technologies to optimize the energy performance for the net zero energy home. *Energy and Buildings, 153*, 262-274.
H4	Beaudin, M & Zareipour, H. (2015). Home energy management systems: A review of modelling and complexity. *Renewable and Sustainable Energy Reviews, 45*, 318–335
H4	Bozchalui, M. C., Hashmi, S. A., Hassen, H., Canizares, C. A., & Bhattacharya, K. (2012). Optimal operation of residential energy hubs in smart grids. *IEEE Transactions on Smart Grid, 3*(4), 1755-1766.
H4	Erdmann, L. & Hilty, L. M. (2010). Scenario analysis: exploring the macroeconomic impacts of information and communication technologies on greenhouse gas emissions. *Journal of Industrial Ecology, 14*(5) 826-843.
H4	Ilic, M., Black, J. W., & Watz, J. L. (2002, January). Potential benefits of implementing load control. In *2002 IEEE Power Engineering Society Winter Meeting. Conference Proceedings* (Cat. No. 02CH37309) (Vol. 1, pp. 177-182). IEEE.
H4	Jin, X., Baker, K., Christensen, D., & Isley, S. (2017). Foresee: A user-centric home energy management system for energy efficiency and demand response. *Applied Energy, 205*, 1583-1595.
H4	Li, N., Chen, L., & Low, S. H. (2011, July). Optimal demand response based on utility maximization in power networks. In *2011 IEEE power and energy society general meeting* (pp. 1-8). IEEE.
H4	Louis, J. N., Caló, A., & Pongrácz, E. (2014). Smart houses for energy efficiency and carbon dioxide emission reduction. *Energy*, 44-50.
H4	Nilsson, A., Lazarevic, D., Brandt, N., & Kordas, O. (2018). Household responsiveness to residential demand response strategies: Results and policy implications from a Swedish field study. *Energy policy, 122*, 273-286.
H4	Paatero, J. V., & Lund, P. D. (2006). A model for generating household electricity load profiles. *International Journal of Energy Research, 30*(5), 273-290.
H5	Jenkins, D. P., Tucker, R., & Rawlings, R. (2009). Modelling the carbon-saving performance of domestic ground-source heat pumps. *Energy and Buildings, 41*(6), 587-595.
H5	Sivasakthivel, T., Murugesan, K., & Sahoo, P. K. (2014). A study on energy and CO_2 saving potential of ground source heat pump system in India. *Renewable and Sustainable Energy Reviews, 32*, 278-293.
H5	Yuan, S., Stainsby, W., Li, M., Xu, K., Waite, M., Zimmerle, D., ... & Modi, V. (2019). Future energy scenarios with distributed technology options for residential city blocks in three climate regions of the United States. *Applied Energy, 237*, 60-69.
H6	Beattie Passive (2017). *Case Study: Retrofit for Social Housing - Solihll, Birmingham* [online]. Beattie Passive, Norwich, UK. https://www.beattiepassive.com/projects/solihull-deep-retrofit-for-social-housing/

H6	Energiesprong (2015). *Transition Zero*. http://transition-zero.eu/wp-content/uploads/2016/09/EnergieSprong_UK-Transition_Zero_document.pdf
H7	Fremstad, A. (2017) Does Craigslist Reduce Waste? Evidence from California and Flordia. Ecological Economics 132, 135-143.
H8	Chakravarty, P., & Gupta, A. (2013). Impact of energy disaggregation on consumer behavior., in Behavior, *Energy and Climate Change Conference (BECC). UC Berkeley, Sacramento CA, 19th Nov. 2013*.
H8	Ehrhardt-Martinez, K., Donnelly, K. A., & Laitner, S. (2010, June). *Advanced metering initiatives and residential feedback programs: a meta-review for household electricity-saving opportunities*. Report Number E105. Washington, DC: American Council for an Energy-Efficient Economy (ACEEE).
H8	McCalley, L. T., & Midden, C. J. (2002). Energy conservation through product-integrated feedback: The roles of goal-setting and social orientation. *Journal of Economic Psychology, 23*(5), 589-603.
H8	Sokoloski, R. (2015). *Disaggregated electricity consumption: using appliance-specific feedback to promote energy conservation*. M.A. California State University San Marcos, 2nd Jul. 2015.
H8	Spagnolli, A., Corradi, N., Gamberini, L., Hoggan, E., Jacucci, G., Katzeff, C., ... & Jonsson, L. (2011). Eco-feedback on the go: Motivating energy awareness. *Computer, 44*(5), 38-45.
H8	Tiefenbeck, V., Wörner, A., Schöb, S., Fleisch, E., & Staake, T. (2019). Real-time feedback promotes energy conservation in the absence of volunteer selection bias and monetary incentives. *Nature Energy, 4*(1), 35-41.
H8	Ueno, T., Sano, F., Saeki, O., & Tsuji, K. (2006). Effectiveness of an energy-consumption information system on energy savings in residential houses based on monitored data. *Applied Energy, 83*(2), 166-183.

2023

Decarbonizing Global Building Sector- Understanding the potential of net-zero building sector

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Executive summary:

To keep the global warming potential well below 1.5 degrees, building sector emission reduction would play pivotal role. Especially, with the pandemic and then Ukraine-Russia war, demand side particularly plays a crucial role in achieving the net-zero transition. However, with the increasing growth of population, urbanization rate, and floor area, reducing energy demand and associated emissions without disrupting individual comfort is challenging. 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. However, despite the significance of the building sector, the data availability in terms of projecting future energy demand of the building sector as well as analyzing energy demand reduction potential of the building sector is limited. Furthermore, data for regional demand, and urban sector often not calculated, hence we do not have much empirical evidence on the regional potential of the building sector.

Thus, this study provides a set of 'what if' scenarios to assess the potential demand and associate emission reductions of the building sector globally as well as regionally under different policy packages by implementing high-efficiency demand measures. To be more explicit, this paper examines the potential for onsite energy supply and future energy demand in eleven important global locations in order to assess the feasibility of achieving net-zero building sector through high-efficient sustainable building legislation. Furthermore, this study provides an estimate of carbon, and energy 'lock-in's in case best building practices are not implemented globally. The findings of the study show that best building practices globally, energy demand of the building sector can be reduced by 74% compared to 2022 levels globally. The regional values show similar trends, for instance, energy demand for the Western Europe and North America region can be reduced by 92%, and in Pacific OECD it can even be reduced by 96%. However, if the best practices are not followed, then a growth of 80% is estimated by 2060 in comparison to 2022 global building energy demand levels. Furthermore, the study also shows that if the best practices are not followed and instead, even the existing building practices are adhered, globally 130% of energy could be 'locked-in' between 2022-2060 which could have been avoided. This pathway towards high-efficiency or net-zero is ambitious in its assumptions and requires strong policy support. The modelling results further show the significance of the building sector by estimating the onsite rooftop solar production- more precisely, rooftop thermal and power production potentials of the building sector is estimated to be 71.6 petawatt-hour (PWh) and 31.5 PWh respectively by 2060. Lastly, by analyzing the onsite energy production and energy demand of the building sector, this study assess the net-zero potentially for each of the 11 regions across the world to explore the possibility of decarbonizing the global building sector by 2060. By analyzing the annual and hourly energy demand and supply profiles of the global and regional building sector, this study illustrates the potential for net-zero building sector. The study's conclusions demonstrate that net-zero potentiality can be attained in the future with the implementation of best building practices such as deep-energy renovation, and high-efficiency building construction across the world.

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1. Background and introduction:

1.1 Global energy trends in the pre and post COVID era

The global energy demand has been increasing substantially, except for 2020 when an unprecedented decline of 4.5% decline is observed due to COVID pandemic, and then 2021 it is increased by 5 and with the increasing trend it is indeed challenging to meet the 1.5-degree goal set during the Paris agreement in 2015 (Enerdata, 2022; Newell et al., 2021). To meet this energy demand, the majority of energy production comes from burning fossil fuels which accounts for around three-quarters of global greenhouse gas (GHG) emissions (Masson-Delmotte, 2018). Global GHG emissions from energy remain almost same at 37 GtCO2eq in 2019 (IEA, 2021). Energy production from the fossil fuel is not causing climate change, but it also causes substantial damages to the human health by emitting several air pollutants- precisely, it is estimated at least five million deaths are attributed to air pollution each year (Ritchie et al., 2022). The largest energy consumers such as Iceland, Norway, Canada, the United States, Oman, Saudi Arabia and Qatar consume 100 times more energy per person on an average than some of the poorest countries (Ritchie et al., 2022) (Figure 1).

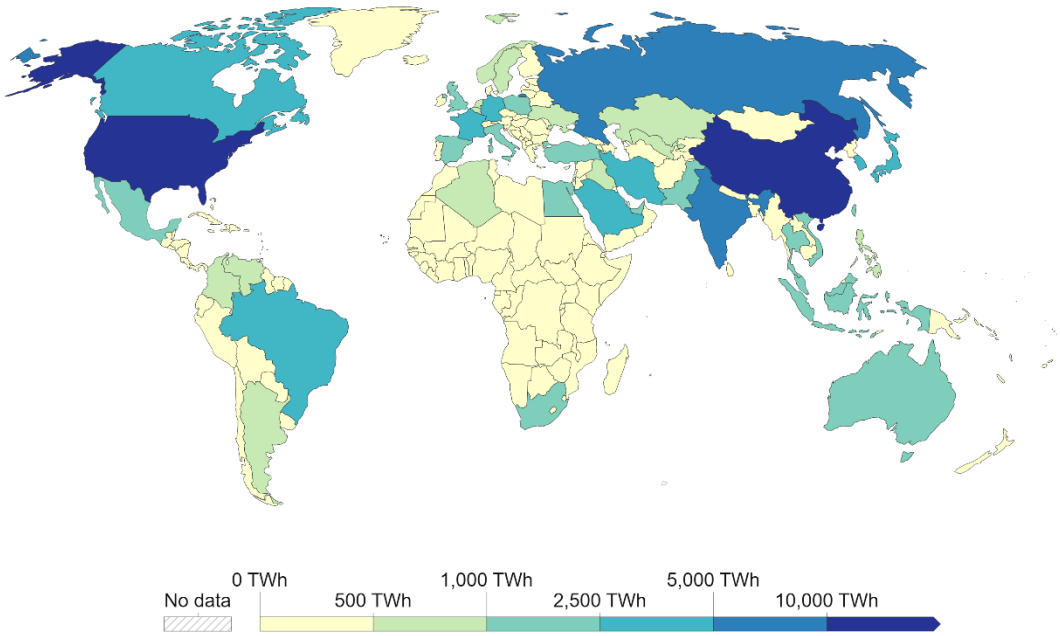


Figure 1. Primary energy consumption in Terawatt hours (TWh) across the World in 2021 (Ritchie et al., 2022)

However, the dynamics of the global energy market has changed drastically due to Ukraine-Russia war in 2022. For instance, the growth in electricity demand is slowing significantly, and it is expected to slow to 2.4% by the end of 2022 (IEA, 2022a). Although post-COVID electricity growth in 2021 was about 6% mostly due to strong economic recovery, in 2022, due to slower global economic growth, and higher energy prices, the electricity growth is expected to be less compared to 2021 (IEA, 2022a).

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The market of natural gas is especially in turmoil due to high gas prices and supply constraints. In most countries, natural gas is majorly replaced by coal-fired power plants (Hosseini, 2022). For instance, in Europe, governments deferred phase-outs of the coal plants and elevated restrictions to increase the availability of coal generation, hence, gas consumption has reduced which improves the security of supply (IEA, 2022a). The Russia-Ukraine war contributes 12% to the global energy trade, among which 16% to the global coal trade, 11% to the global oil trade and 10% to the global gas trade (Zhou et al., 2023). European Union received 45% of the natural gas from Russia to meet 40% of its gas demand in 2021 (IEA, 2022b). This share has increased in recent years, as European domestic natural gas production has declined. Majority of this imported energy is used in the building sector for space heating, cooling, and cooking (IEA, 2022a).

As per the latest Commodity market outlook report published by the World Bank, due to the Russia-Ukraine war, the energy prices globally are expected to grow by 50% in 2022 (World Bank, 2022). This increase in energy price along with the post-COVID effects may push the global economy to a stagnation (Zakeri et al., 2022). As a way-out to solve the energy crisis, governments tend to invest more on fossil-fuel based energy, more precisely, oil- and coal-fired electricity generation, along with increasing interest in renewable and nuclear options (IEA, 2022c). The crisis can be best understood by analyzing the historic data which shows that investment in fossil fuel dropped after 2014-2015, and the investment in clean energy has peaked recently in 2021. Figure 2 below presents the

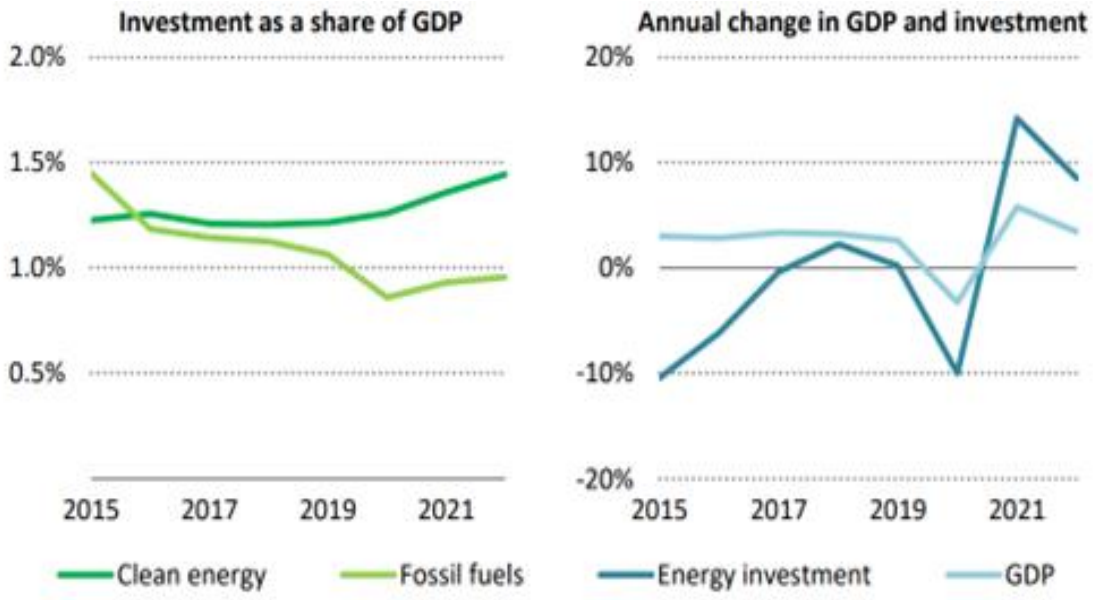


Figure 2. Changes of GDP as well as investment in total energy, clean energy and fossil fuels between 2015 and 2022 (IEA, 2022c)

This data also suggests that net-zero target set by different countries with 2050 timeline faces substantial challenges due to energy crisis and due to the paths taken to tackle energy crisis. Although, renewable energy solutions, along with energy storage and carbon removal technologies have received lot of attention to tackle this crisis, there are still uncertainties related to the outcome, and resource requirement of these technologies (Creutzig et al., 2018). In fact, many of the technologies, especially carbon removal technologies, have a high lifecycle material footprint (Madhu et al., 2021). Thus, considering all the factors, it is often argued that demand side measures could be the most effective solution to tackle the energy crisis without increasing material footprint and uncertainties

(Zakeri et al., 2022). The demand side solutions also provide flexibility to the energy system which makes the transition towards net-zero system much faster and cheaper (Chatterjee et al., 2022b; Patt et al., 2019).

1.2 Contribution of the building sector to the energy and CO_2 emission

In 2021, the building sector consumed 135 EJ of energy and emitted 10 Gt of CO_2 on global level (IEA, 2022d) (Figure 3). By considering the embodied energy use and emission, the above numbers could be 6 to 10% higher. Consequently, nowadays about 37% of the global energy consumption and CO_2 emission is attributable to building-related material production and different end-use activities (e.g., heating, cooling, lightning and cooking) (UNEP, 2022). Despite the reductions due to the COVID crisis over 2020, the global energy consumption and CO_2 emission increased by 4 and 5% in 2021, in coherence with trends observable for the entire energy sector (IEA, 2022d). It results in the highest historical CO_2 emission of buildings, which indicates that major efforts are needed to reach decarbonization goals and be able to tackle the adverse effects of climate change.

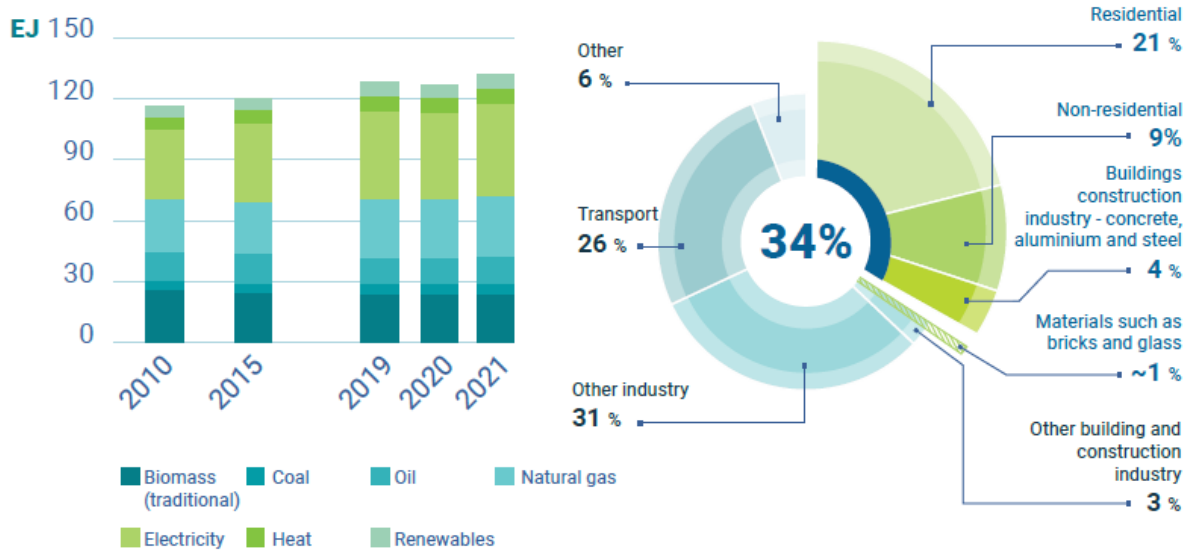


Figure 3. Total energy consumption of the building sector by fuel types (left) and total energy consumption shares of each sector, including detailed decomposition for the building sector (right) (UNEP, 2022)

To limit the global temperature rise well below 1.5°C by 2050, the building sector must shift to carbon-neutral track and significantly reduce the use of fossil fuels over the next decades. As the Net Zero Scenario of the International Energy Agency (IEA) estimates, both the energy consumption and the share of fossil energy sources must be decreased by around 25 and 40% to be compatible with the Paris Agreement (IEA, 2022d). However, there is a consensus in the scientific community that without more ambitious and comprehensive interventions, finding the right track is unrealistic (Gielen et al., 2019; Rosenow et al., 2017; Zakeri et al., 2022). The urgency of scaling up current policies is well demonstrated by the Global Buildings Climate Tracker (GBCT) measure that is an index composed of indicators for CO_2 emission, energy intensity, renewable energy share, building regulations, energy efficiency investments, green building certifications and different building attributes of the Nationally Determined Contributions (UNEP, 2022). By summarizing the weighted influences of these indicators,

the GBCT was estimated to be 8.1 point (0: worst case; 100: best case), showing a 3.2-point decrease from the preceding year due the bounce back of the economy after the global health crisis. The (UNEP, 2022) report also adds that the optimal value should be higher than 17.1 point by now. The clear message of the above numbers is that though the COVID closures have driven the energy and building sector into a better direction because of changes in the consumption patterns (Jiang et al., 2021), these tendencies seem to be outliers in the time series of energy demand and CO_2 emission, and the emerging opportunities might have not been exploited in the desired way.

In the meantime, the global floor space has been showing a clear expansion over the years (IEA, 2022d) and is estimated to continue its increasing trend by 2050 (Figure 4), particularly in Latin America, Africa and South Asia (Deetman et al., 2020). As an IEA report predicts (IEA, 2019), the majority of the floor area growth will take place in countries where there is no official building energy codes or the codes are prescribed on a voluntary basis. Without having suitable building codes worldwide, however, it seems to be a quite uncertain mission to drastically increase the energy efficiency of buildings in the future decades. Consequently, the emerging economies highlighted above must soon turn their attention to support (both in financial and regularization level) sustainable technologies (e.g., solar, hydrogen, heat pumps) for new and existing buildings (Gielen et al., 2019; UNEP, 2022).

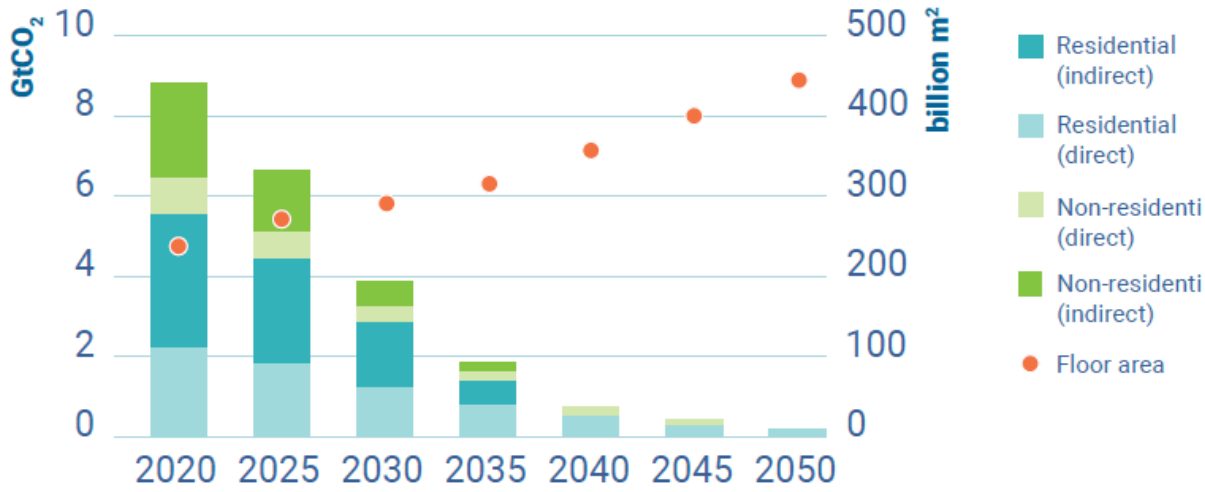


Figure 4. Projected change in floor area and the corresponding CO_2 emission by building types between 2020 and 2050 (UNEP, 2022)

In 2020, the buildings-related energy consumption was fueled mostly by electricity (33%), followed by biomass (24%) and natural gas (22%) (González-Torres et al., 2022). The share of onsite renewables peaked only around 2%. One year later, the renewables increased up to 6%, while the share of other fuels has not shifted substantially (IEA, 2022e). Over the next decade, however, the share of fossil fuels in the energy should be lowered by 40% (including the complete elimination of biomass-based and significant reduction of coal-based energy consumption) and being replaced by carbon-free energy sources (IEA, 2022d). New, energy efficient technologies could have large impact in reducing energy demand for space heating (53.4%), appliances (19.1%) and hot water (15.9%), being the responsible for more than two third of the total residential energy consumption in 2019 (IEA, 2022f) (Figure 5). Like the LED for lighting, energy efficient televisions, refrigerators and washing machines for appliances as well as heat pumps indicate that most of the technologies are already accessible to be able to get closer to the milestones needed to be in line with the right decarbonization track (IEA,

2022g). Nevertheless, several barriers (e.g., availability, initial cost, cost-effectiveness and lifetime) are required to be overcome and more research is needed to scale up those technologies (Belussi et al., 2019). In parallel, the rapidly evolving cooling need (with an annual growth of 4% since 2000) (IEA, 2022h) emerges as an additional burden, which should be satisfied by highly efficient passive (e.g., cool roof and natural air/water cooling) and active solutions (e.g., refrigerant cooling and natural air/water cooling) (Belussi et al., 2019).

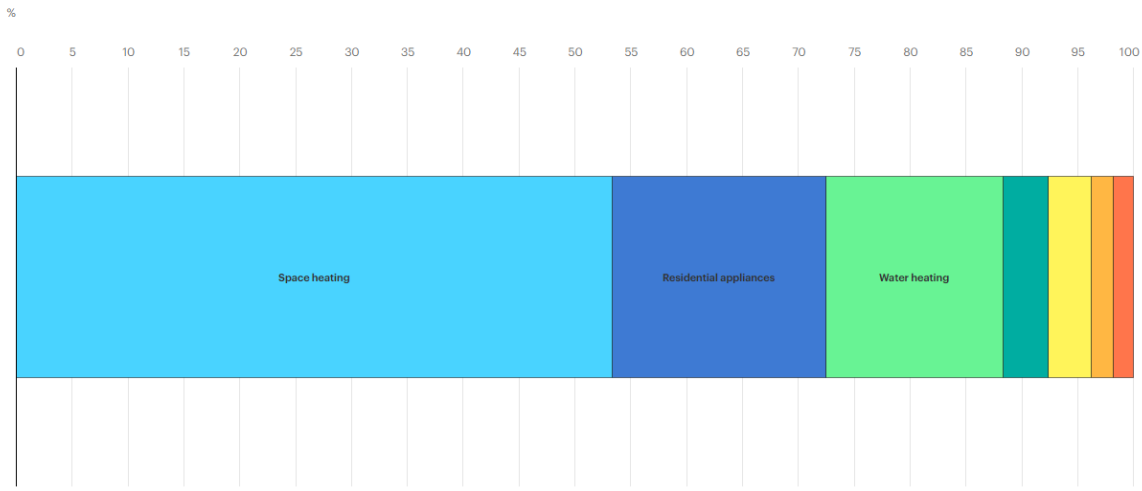


Figure 5. Shares of end-uses for the residential energy consumption in the 24 IEA member countries in 2019. End-uses without caption: cooking (dark green), space cooling (yellow), lighting (orange) and other (red) (IEA, 2022f).

Since cities are the key contributor to climate change, accounting for 75% of global C02 emissions, the building sector in cities/urban areas needs to be emphasized while planning emission reduction policies (UNEP, 2023). More precisely, the thermal energy demand of the building sector will be dominated by the urban residential building sector which is estimated to account 85% of the thermal energy increase, 70% of which can be attributed to cities in developing countries (Ürge-Vorsatz et al., 2015). There are many reasons, for instance, urbanization, population growth, increase in comfort standards and changing lifestyles etc. which attributes to this increase in demand in the urban areas (Grove-Smith et al., 2018). Furthermore, to achieve net-zero building sector by 2050, the direct and indirect emission of the global building sector needs to be reduced by 50% and 60% respectively by 2030 (UNEP, 2022). Despite this dynamic change and nature of building sector, especially in the urban building sector, the data availability in terms of projecting future energy demand of the building sector as well as analyzing energy demand reduction potential of the building sector is limited. Furthermore, data for regional demand, and urban sector often not calculated, hence we do not have much empirical evidence on the regional potential of the building sector. Thus, this study uses two bottom-up models to analyses the net-zero potential of the building sector by considering the current socio-economic trends and data. Particularly, this study aims to provide insights on future global thermal energy demand potential under different scenarios including the baseline scenario and timeline (2022-2060) in the context of net-zero target. This study puts a particular emphasis on the urban building sector by calculating the thermal energy demand of the global urban thermal energy demand and its associated emissions under different policy frameworks.

1.3 Aim and structure of the report

The aim of this report is to explore the potential of possible global net-zero building sector under different policy frameworks, and to assess the potential carbon lock-in in case we are settling with less ambitious policies. To achieve the aim of this study, this research has following five key objectives:

1. Calculate and analyze the annual thermal demand of the global building sector across four different policy scenarios including business as usual, high efficiency as well as low efficiency scenarios.
2. Calculate and analyze the hourly thermal demand of the global building sector to understand the peak demand for each of the regions across globe under different policy scenarios including business as usual, high efficiency as well as low efficiency scenarios.
3. Calculate and analyze both the annual and hourly onsite thermal and electric solar energy potential from the building sector for all the key regions across the globe.
4. Assess the net-zero potential of the global building sector by analyzing both the annual and hourly demand and onsite energy supply profiles under different policy frameworks.
5. Calculate and analyze potential carbon and energy lock-in of the building sector globally across 11 regions by 2060 for different policy framework.

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.

This report is organized into six sections. Section 1. introduces the motivation behind this study by introducing the recent pre and post-pandemic trends of energy demand, and importance of the building sector to contribute to the science of climate change mitigation measures. The first section further discusses the key trends of energy demand and supply globally. Section 2. then outlines the methodological framework of this research by presenting two bottom-up models namely high-efficiency building (HEB) model and Building Integrated Solar Energy (BISE) model used in this study. In Section 3., we present the results from HEB model of the thermal energy demand of the global building sector. Section 4. then presents the onsite solar energy production potential under different policy framework. Based on the results presented in Sections 3. and 4., Section 5. analyses the net-zero potential and carbon-lock potential of the global building sector under different policy frameworks. Lastly, Section 6. discusses the results in the context of global energy demand reduction and climate change mitigation, and also concludes the study by discussing the policy relevance of the results from two building models.

2. Methodological framework

2.1 Methodological introduction of the HEB model

As it is discussed in our recent publications (refer to Chatterjee et al., 2023, 2022a; Teske et al., 2022) HEB model calculates energy demand and CO_2 emissions of the residential and tertiary building sector until 2060 under three different scenarios to investigate the potential of the building sector to mitigate climate change through various opportunities. HEB model was originally developed in 2012, and then upgraded to calculate annual and hourly energy demand and CO_2 emissions of the residential and tertiary building sector until 2060 under four different scenarios (Urge-Vorsatz, 2012; chatterjee et al. 2022). HEB 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, 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 and hourly resolution for 11 key regions which cover the world.
Chatterjee et al. (2022) study discusses that HEB model is built 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 also discussed in Chatterjee et al., 2023, 2022a studies:

1. **Deep Efficiency Scenario:** Deep efficiency scenario demonstrates the potential of state-of-the-art construction and retrofit technologies that can substantially reduce energy consumption of the building sector and hence reduce CO2 emissions 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 implementation of 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 the baseline and retrofit buildings consume around 10% less than standard existing buildings for space heating and cooling, while most new buildings have a higher level of energy performance than in Moderate scenario due to lower compliance with Building Codes.
4. **Towards Net Zero Scenario**: The last scenario models the potential of deploying “Net Zero Energy

Buildings" − buildings that can produce as much energy locally through the utilisation of renewables as they consume on an annual balance. 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 HEB scenarios (Chatterjee et al., 2023)

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.

2.1.1 Climate classification

The magnitude of energy demand as well as the structure and timing of the energy consumption of buildings in each region are strongly influenced by such climatic factors as ambient air temperature, humidity and solar radiation (Deroubaix et al., 2021; Taleb et al., 2020). To capture and better understand the climatic effect on energy demand (and supply) both on spatial (i.e., regional) and temporal (i.e., annual and hourly) level, a detailed climate classification scheme was developed that, on the one hand, incorporates high-resolution climate reanalysis data and that, on the other hand, takes the most relevant climatic factor into account.

Although the HEB (and the BISE) model has already included a climate classification in earlier versions, relying on outdated input data (Petrichenko, 2014), the aim of the new procedure was to refine the boundary of the "old" zones and explicitly consider the shifts in the distribution of the climatic parameters occurred over the previous years.

The updated climate classification is based on the MERRA-2 (The Modern-Era Retrospective analysis for Research and Applications) climate reanalysis database (Gelaro et al., 2017) that was constructed by the NASA's Goddard Earth Sciences (GES) Data Information Services Centre (DISC)[1]. The advantage of climate reanalysis data is that they are composed of quality-controlled, assimilated observations and modeling information to reconstruct the past climate as accurately as possible. Of the existing climate reanalysis databases, the MERRA-2 has been proven to be reliable in reproducing several climatic parameters across the World (Arshad et al., 2021; Keller and Wahl, 2021; Kim et al., 2018).

In order to select a suitably long period for the classification process and include the current tendencies of our changing climate, the MERRA-2 data were retrieved for the years between 2010 and 2020. Since the climate system of the Earth has substantial complexity, a multivariate approach was applied for the classification. Similar to the earlier versions of the HEB's climate system, the ambient air temperature and mean temperature and relative humidity of the warmest month were selected as factors relevant for segregating different climate zones. As the "degree-days method" (cooling degree days – CDD, heating degree days – HDD) is a widely-used and accepted way of estimating the temperature-dependency of energy needs for space heating and cooling need of buildings under different climates (Deroubaix et al., 2021; Meng and Mourshed, 2017; Wang and Chen, 2014), firstly indices for CDD and HDD were estimated on spatial basis using the 10-year mean of hourly MERRA-2 temperature data as:

$$CDD = \sum_{i=1}^{n} T_{base} - T_{daily,i} \quad (1)$$

$$HDD = \sum_{i=1}^{n} T_{daily,i} - T_{base} \quad (2)$$

$$T_{daily,i} = \frac{T_{max,i}+T_{min,i}}{2} \quad (3)$$

where T_{base} is the base or set-point temperature, $T_{daily,i}$ is the mean daily ambient air temperature and $T_{max,i}$ ($T_{min,i}$) is the daily maximum (minimum) temperature on a given (i) day of a year. By definition, the base temperature expresses the outdoor air temperature at which the indoor temperature is in a comfortable range without the use of any mechanical heating and cooling (Lee et al., 2014). For this reason, the T_{base} is influenced by the thermal sensation of building occupants (e.g., thermostat set-point temperature) as well as by internal heat generation, solar gain and building properties (e.g., heat transfer coefficient) (Bhatnagar et al., 2018). It means, therefore, that the T_{base} values have varying ranges as per regions, climate zones and building types. Nevertheless, for simplicity, usually one T_{base} value is used for the calculation of CDD and HDD in worldwide studies (e.g., Spinoni et al., 2018), thus our recent estimation also considered single T_{base} in deriving the CDD and HDD maps. Based on Sadeqi et al. (2022), 22°C and 18°C were substituted into Equations 1-2.

The determination of the CDD and HDD values in each grid point (in appr. 736×361 points) was followed by the statistical analysis of the indices. Precisely, inspecting the histograms, kernel density functions and box plots (Figure 6) of the CDD and HDD values, more insight could be gained on their corresponding data distribution. To achieve a "first guess" on potential CDD-HDD categories, a multivariate spatial K-means classification was performed (Carro-Calvo et al., 2017) with the SAGA

[1] NASA's GES DISC website: https://disc.gsfc.nasa.gov/

GIS[2] package. For this step, the lowest number of clusters (i.e., CDD-HDD categories) that has to be set in the software was optimized using the Elbow method (Syakur et al., 2018) (Figure 6). This approach showed that there could be at least five CDD-HDD classes based on the derived gridded data.

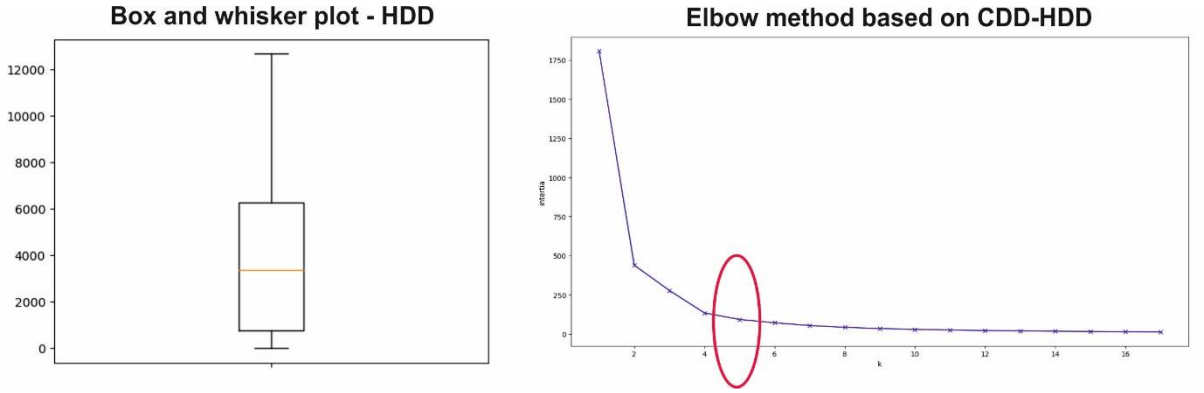


Figure 6. Two examples of the preliminary statistics of CDD and HDD (in °C/year) data used for the classification

In the next stage, additionally to the CDD-HDD data, the mean spatial patterns of the mean relative humidity ($RH_{warmest}$) and air temperature of the warmest month ($T_{warmest}$) were computed, too. The $RH_{warmest}$ distribution was derived indirectly from the specific humidity (q) values of the MERRA-2 dataset using the expressions below:

$$e = \frac{q}{0.622} \cdot p \quad (4)$$

$$e_s = 6.11 \cdot exp\left(\frac{7.5 \cdot T}{237{,}3+T}\right) \quad (5)$$

$$RH = 100 \cdot \frac{e}{e_s} \quad (6)$$

where p is the surface air pressure in hPa, e is the vapor pressure in hPa, e_s is the saturation vapor pressure in hPa and T is the 2-m air temperature in °C.

In the classification, the role of these variables was to find climate zones in which high RH and $T_{warmest}$ results in strong thermal stress and need for dehumidification of building interiors. The Humindex (Masterson and Richardson, 1979) measure is often applied to describe the level of thermal discomfort due to air temperature and humidity, so this index was found to be appropriate to assign an $RH_{warmest}$-$T_{warmest}$ pair above which building occupants may intend to switch the HVAC system on to cool and dehumidify their indoor space. Under conditions with 75% of $RH_{warmest}$ and 25°C of $T_{warmest}$ the Humindex has values in a range between 38 and 48, which suggests moderate and great discomfort during the daytime (Baum et al., 2009) of the warmest month.

[2] https://saga-gis.sourceforge.io/en/index.html

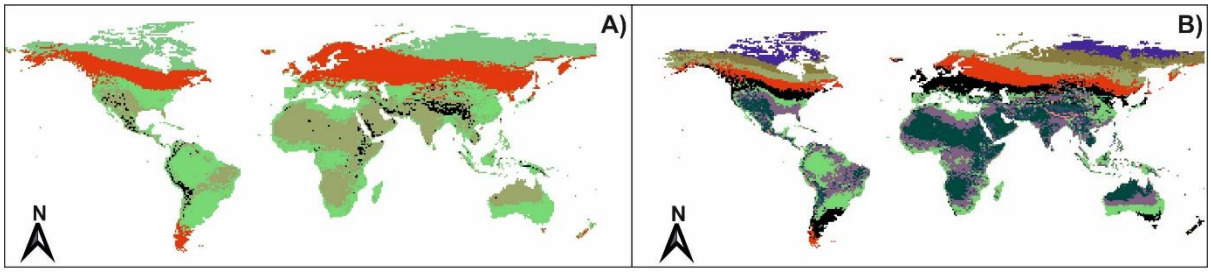


Figure 7. Results of preliminary CDD-HDD-based climate classification by considering 5 (map A) and 10 (map B) categories

After combining the preliminary CDD-HDD classes with the criteria for the $RH_{warmest}$ and $T_{warmest}$, the first iteration of the classification process was executed. By comparing result with other existing climate classifications (e.g., Koppen–Geiger-classification[3]) and by identifying large unclassified territories, the iteration was repeated several times to reduce the extent of unclassified areas and to diversify the classification (Figure 7). Once an acceptable result was achieved, the classified data were spatially post-processed to have a new map with fewer climate class "mosaics" (i.e., classes with small area), by filtering them out using the GPW population database[4]. Precisely, pixels with population less than 1% of the most populous zone were merged with the dominant neighbor climate zone if:

1. this neighbor zone included at least one pixel (*size filter*),
2. this neighbor zone was not surrounded by the same class (*isolation filter*).

At the end of the climate classification process, 19 zones depicted in Figure 8 and summarized in Table 2 were generated and implemented into the HEB (and BISE) model. It can be observed that the classification scheme includes four-four categories where either heating or cooling demand (from low to very high) emerges. There are 10 categories where heating and cooling coexists in different magnitude. The system also contains 4 classes where cooling and heating-cooling demand along with dehumidification need might occur. Furthermore, there is one category to which areas with insignificant heating and cooling demand belong (Table 2). As Figure 7 illustrates, vast majority of the classified domain can be characterized by only heating demand, particularly in mountainous and high-latitude regions. In the mid latitudes, the "mixed" classes dominate, while in the lower latitudes, two "climate belts" can be found based on our classification scheme. In the Subtropics, classes with significant cooling demand are seen. On the other hand, climate zones with dehumidification could appear around the tropical regions.

[3] http://koeppen-geiger.vu-wien.ac.at/present.htm
[4] http://sedac.ciesin.columbia.edu/data/collection/gpw-v4/sets/browse

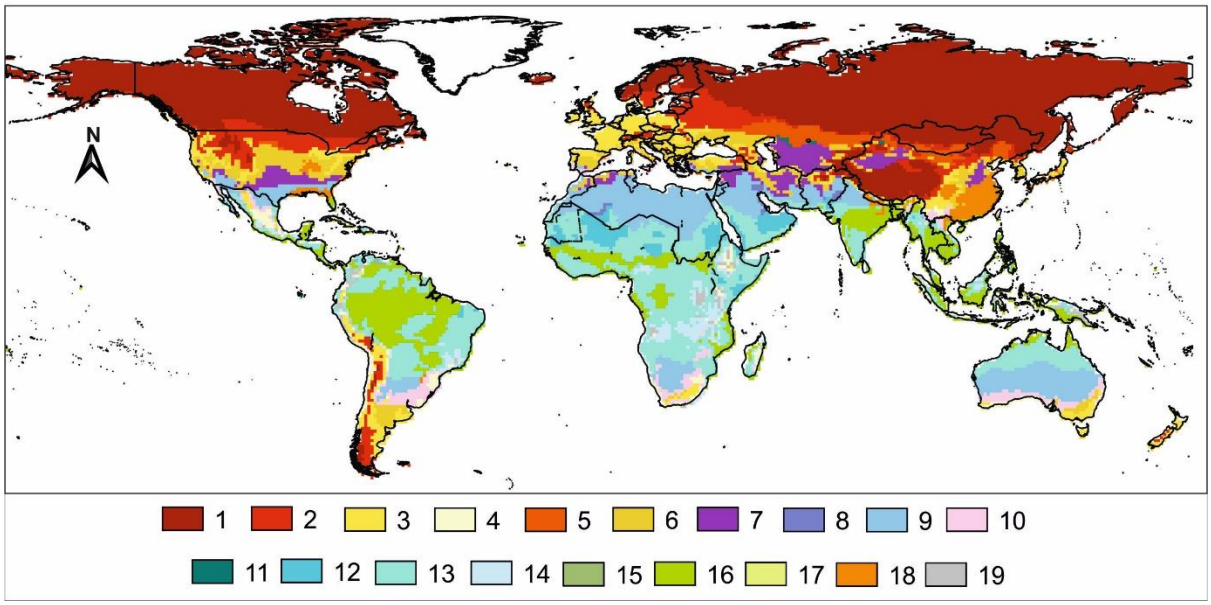


Figure 8. Spatial distribution of the climate classes used in the HEB and BISE model. The illustrated classes are the same found in Table 2. The black line indicates the borders of the geographical units used in HEB, not the borders of countries!

Table 2: The climate classification shceme used in the HEB and BISE models. In the columns the climate classes (CIDs) and their corresponding classification criteria (for CDD – cooling degree days, HDD – heatind degree days, $RH_{warmest}$ – relative humidity of the warmest month and $T_{warmest}$ – mean daily air temparature fo the warmest month) are indicated.

Category (CID)	**CDD**	**HDD**	**$RH_{warmest}$**	**$T_{warmest}$**
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	-	-

2.2 Methodological introduction of the BISE model

2.2.1 General description

The BISE (Building Integrated Solar Energy) model was developed to be an algorithm-based modeling framework in which both geospatial and statistical approaches are used. The main goal of this hybrid energy supply model is to predict the technical potential of onsite thermal and electric energy production on the rooftops of different building types by considering PV and PV/T systems (Molnár et al., 2022; Petrichenko, 2014; Petrichenko et al., 2019).

The BISE consists of 11 socio-economic regions spanning the entire Globe and several focus countries (i.e., EU Member States and the United Kingdom). The regions considered are Sub Saharan Africa (AFR), Centrally Planned Asia (CPA), Central and Eastern Europe (EEU), Former Soviet Union (FSU), Latin America (LAC), North Africa and Middle East (MEA), North America (NAM), Pacific OECD countries (PAO), Other Pacific Asia (PAS), South Asia (SAS), and Western Europe (WEU). It has a time frame between 2022 and 2060, which ensures the possibility of long-term outlook with regard to the building sector (Molnár et al., 2022).

In the BISE, there is a detailed building classification system that includes eight building types (i.e., single- and multifamily buildings, educational buildings, hotels/restaurants, hospitals, retails, office, and other buildings) and five building vintages (i.e., standard/existing, new, retrofitted, advanced new, and advanced retrofitted). For the analyzed geographical entities, the share of building types and building vintages relies on GDP and population data while prescribing certain retrofit and demolition rates (Petrichenko et al., 2019). In the model, the building stock is projected on an annual basis.

It must also be highlighted that the above-mentioned building categorization scheme in the BISE is estimated externally from the High Efficiency Building (HEB) model (Chatterjee et al., 2022a; Güneralp et al., 2017; Urge-Vorsatz, 2012). More precisely, for each of the considered disaggregation level (i.e., region, climate zone, urban/rural/slum, main building type, building subcategory and building vintage), the BISE implements the respective HEB shares of floor area and different roof to floor ratios

(Table 3) to increase or decrease the roof area over the simulation period, since the total roof area is quantified directly only for the first year of the simulation era (Molnár et al., 2022) by the BISE. The floor area estimations are obtained from the disaggregation of input data based on the building classification detailed above, the total required floor area is determined to satisfy the year-specific population and GDP needs, and the yearly dynamics of retrofit and new floor area. For details on the HEB-related floor area estimations see Section 2.1.

Table 3. Roof to floor ratios by regions and building types used in the BISE model (Petrichenko et al., 2019)

Region	Residential		Commercial/Public				
	Single family	Multi-family	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

2.2.2 Estimation of total and suitable roof area

The model consists of three major groups for input parameters. These groups rely on information for meteorological, technological and building rooftop-related factors.

The rooftop-related variables can be split into two segments, namely the total and solar-compatible (suitable) roof area estimations. The estimation of the total roof area is first based on the raster grids of the Global Human Settlement Layer [5](GHSL) developed by the Joint Research Centre (JRC) and the DG for Regional and Urban Polity of the European Commission, combined with building cadastre maps acquired via the INSPIRE Geoportal. The GHSL data is used for the 11 regions of the BISE model.

For the individual European Member States, the GHSL-based building footprint dataset was updated with values derived from the open building vector layers of OpenStreetMap[6] (OSM) and Microsoft Global Building Footprint[7] (MGBF) databases. The OSM building polygons were originally created by using aerial imagery, surveys and other freely licensed geospatial databases, while the MGBF data was derived from Airbus and Maxar imagery applying semantic segmentation techniques. The latter data

[5] https://ghsl.jrc.ec.europa.eu/data.php
[6] https://wiki.openstreetmap.org/wiki/Main_Page
[7] https://github.com/microsoft/GlobalMLBuildingFootprints

has a precision of 94.3% for Europe, therefore both databases were proven to be great basis for building footprint estimation.

The conversion of building footprint to total roof area in the BISE depends on the shape and tilt angle of rooftops. For single and multifamily buildings, the ratio of flat and tilted roofs was considered to be 25% and 75%, respectively (Molnár et al., 2022). For commercial and public buildings, all roofs were assumed to be flat.

To calculate the available roof area for solar energy production, first the tilt angles of the residential rooftops (in 75%), without having reliable global data for this parameter, were characterized with tilt angles provide the highest solar energy radiation over the year. The geographical dependence of this optimal tilt angle (β) was calculated with polynomial equations based on the latitude (ϕ in decimal degrees) and the hemisphere (Jacobson and Jadhav, 2018).

$$\beta_{NORTH} = 1.3793 + \varphi[1.2011 + \varphi(-0.14404 + 0.000080509\varphi)] \quad (1a)$$

$$\beta_{SOUTH} = -0.41657 + \varphi[1.4216 + \varphi(0.024051 + 0.00021828\varphi)] \quad (1b)$$

By considering the estimated β values, the total roof area was then reduced to obtain the are available for solar energy production (i.e., PV and PV/T), using the utilization factor defined by Romero Rodríguez et al. (2017), which accounts for shadows (C_{SH}), protected areas (C_{PROT}), construction areas (C_{CON}), service areas (C_{SA}), azimuth (C_{AZ}), slope angle (C_{SL}), panel separation (C_{GCR}), and occurrence of other solar panels (C_{PV}) or collectors (C_{TH}). The values summarized in Table 4 were determined based on literature sources (Byrne et al., 2015; Kurdgelashvili et al., 2016; Romero Rodríguez et al., 2017; Wiginton et al., 2010).

Table 4. Utilization factor to calculate the available roof area for solar production. In the equations, β is the ideal tilt angle and φ is the mean latitude of a region

Coefficient	Flat roof	Pitched tilted roof
C_{CON}	0.8	0.9
C_{PROT}	1	1
C_{SH}	0.7	0.8
C_{SA}	0.97	1
C_{AZ}	1	0.5
C_{SL}	1	Eqs. 1a-b (normalized with mean regional value)
C_{GCR}	$C_{GCR} = \frac{1}{\cos\beta + SBR \cdot \sin\beta}$	1
C_{PV}	1	1
C_{ST}	1	1

For EU countries, we identified the opportunity to use very high-resolution LIDAR (Light Detection and Ranging) data for refining some of the coefficients of the utilization factor, which is expected to lead to the better estimation of the roof area suitable for solar energy production. However, such calculation is quite expensive in data and computation time, LIDAR data was applied in several

investigations (e.g., Jurasz et al., 2020; Walch et al., 2020) to build 3-d building models of real urban areas and to derive crucial information on parameters as shading, roof tilt and orientation.

For this purpose, LIDAR data and OSM building polygons from different urban areas of the EU member states were employed (Figure 9). These urban areas were selected by the following two criteria. First, each city must be located in different climate zones, using our MERRA-based climate classification (please refer to Section 2.1.1). Second, each area must have various building coverage types, which was evaluated relying on the Urban Atlas[8] (UA) surface typology. For a given city, the mean value of each parameter was computed by weighing them with the areas of the UA category for which the parameter was calculated. Thus,

$$S_u = \sum_{i=1}^{n} S_{u_i} \cdot \frac{a_{u_i}}{A_u} \quad (2)$$

where S_u is, for example, the mean fraction of shaded rooftops in an *u* urban area, S_{ui} is the mean fraction of shaded rooftop for building polygons located in an *i* UA surface class in the same *u* urban area, a_{ui} is the summed area of the building polygons located in an *i* UA surface class in the same *u* urban area and AU is the summed area of the building polygons located in the same *u* urban area. From the computed variables (i.e., shading, roof tilt and orientation), we finally used only the mean shading to be able to conserve consistency with the methodology presented at regional U_F.

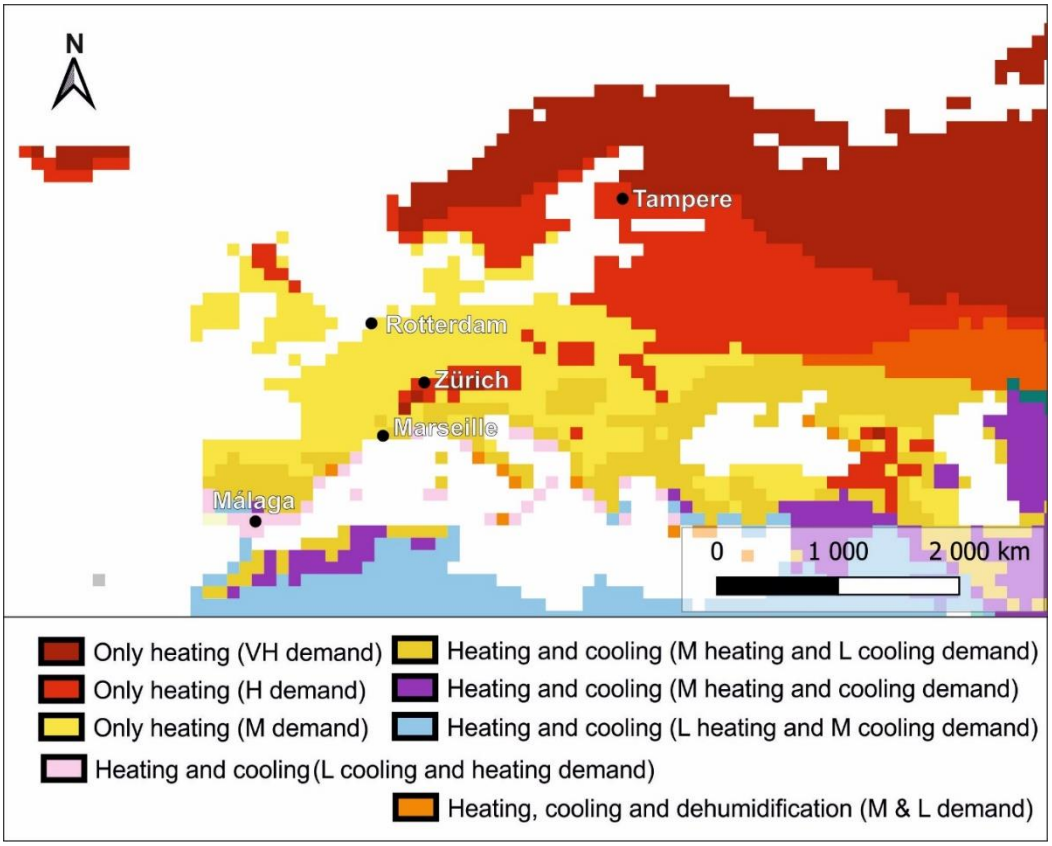


Figure 9. Location of reference urban areas used for LIDAR data processing and found in specific climate zone based on the HEB's climate classification

Finally, it was assumed that the building typology in a given area is mainly influenced by such climatic factors as annual sunshine duration, radiation income, rainfall intensity and share of rain and snow precipitation. In other words, areas with similar climate might have similar roofing characteristics

[8] https://land.copernicus.eu/local/urban-atlas

(Sudhakar et al., 2019). By implementing this assumption, the findings of the LIDAR data processing were extended on the basis of climate zones. Consequently, the values of a zone included in Table 5 were hypothesized to be the same irrespective of the EU countries in which the climate regions are found.

Table 5. Estimated shading over buildings in reference urban areas of specific European climate zones. The CID refers to the climate ID used in the climate classification of our HEB model. Footnotes indicate the data sources for LIDAR data for a given urban area.

Reference urban area	Climate zone (HEB classification)	Other climate zones to extend	Shading (%)
Tampere (Finland)[9]	CID 1 – Only heating (Very high heating demand)	–	61%
Zürich (Switzerland)[10]	CID 2 – Only heating (High heating)	–	42%
Rotterdam (The Netherlands)[11]	CID 3 – Moderate heating demand	–	47%
Marseille (France)[12]	CID 6 – Heating and cooling (Moderate heating and low cooling demand)	CID 7 – Heating and cooling (Moderate heating and cooling demand) & CID 9 – Heating and cooling (Low heating and moderate cooling demand)	38%
Malaga (Spain)[13]	CID 10 – Heating and cooling (Low heating and cooling demand)	CID 18 – Heating, cooling and dehumidification (Low and moderate heating and cooling demand)	29%

Once the U_F is determined for each of the geographical region of interest, the suitable roof area is predicted in the function of total roof area (Equation 4) and utilization factor (Equation 3). It is noteworthy to mention again that the total rooftop area is estimated with the combination of the reference rooftop values (from building footprint calculations, valid for 2022) and floor area tendencies of HEB corrected by roof to floor ratio (Table 3).

$$U_F = C_{PROT} \times C_{SA} \times C_{CON} \times C_{SH} \times C_{AZ} \times C_{SL} \times C_{GCR} \times C_{PV} \times C_{TH} \quad (3)$$

$$RA_{avail_{i,j}} = U_F \times RA_{total_{i,j}} \quad (4)$$

where U_F is the utilization factor, C_{xx} are the corresponding coefficients, RA_{total} is the total roof area in a given *i* year and *j* region and RA_{avail} is the available/suitable roof area in a given *i* year and *j* region.

[9] https://tiedostopalvelu.maanmittauslaitos.fi/tp/kartta?lang=en
[10] https://www.swisstopo.admin.ch/en/geodata/height.html
[11] https://app.pdok.nl/ahn3-downloadpage/
[12] https://geoservices.ign.fr/lidarhd
[13] http://centrodedescargas.cnig.es/CentroDescargas/locale?request_locale=en

2.2.3 Estimation of meteorological inputs

Establishing reliable meteorological databases for the model is important to accurately predict the energy conversion taking place over building rooftops. The algorithms of the BISE requires the estimation of ambient air temperature, wind speed, surface global radiation and top of atmosphere incoming shortwave radiation. Two data sources were combined to derive these variables. First, we applied 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 main advantage of using this database was the hourly availability of meteorological variables, which was essential to capture the intraday course of solar radiation absorbed by PV/T collectors. Relying on 5-year MERRA-2 data [14](2015–2019), a typical meteorological year (TMY) was estimated for each of the parameters. Nevertheless, the relatively long modeling period of the BISE implies a certain change in the magnitude of these inputs due to climate change. In order to be able capture this shift, data from climate projection was added to the TMY fields.

To be precise, the future tendencies of the meteorological inputs were fused with their historic mean values. Technically it meant that hourly slices of the TMY data were transformed into individual profiles, including 8760 time steps in each grid point of each variable. To do so, the following expression was solved (here an example for global radiation – I_{glob} is given):

$$c_{ijk} = \frac{I_{glob,ijk}}{I_{glob,mean,ijk}} \quad (5)$$

where c is the calculated weight, $I_{glob,mean}$ is the daily mean of the global radiation and I_{glob} is the actual global radiation in a given *i* month and *j* day and *k* hour.

Thereafter, climate projection with daily temporal resolution was acquired from the CMIP-6 (Climate Model Intercomparison Project) dataset. By checking the attributes of the available projections, the SSP 1-2.6 experiment (Riahi et al., 2017) of the DKRZ (German Climate Computational Centre; Schupfner et al., 2019) was found to be most appropriate for our purposes. On the one hand, this simulation contained all five BISE inputs in a suitable spatio-temporal resolution (i.e., Δt=1 day and Δx≈100 km). On the other hand, it represented a "middle of the road" scenario in terms of future CO_2 emission, which was picked to avoid the too pessimistic or too optimistic foresight of the climate over the analysis period.

For preparing the DKRZ-based variables to be compatible with the BISE, the c weights of Equation 5 were employed to disaggregate the daily projections to hourly level. In mathematical term, this step was formulated as (here an example for global radiation is given):

$$I_{glob,ijk} = c_{ijk} \cdot I^*_{glob,ij} \quad (6)$$

where I_{glob} is the estimated global radiation, c is the MERRA-based hourly weight of global radiation and I^*_{glob} is the DKRZ-based daily value of the global radiation. It must be noted that before solving Equation 6, the DKRZ files were needed to be re-gridded, using bilinear interpolation, to match the resolution of the two different meteorological datasets. Each of the preliminary steps concerning the meteorological inputs were automatically performed by CDO (Climate Data Operator; Schulzweida, 2019) tool embedded in Python scripts.

[14] NASA (2020). Data collections. https://disc-sci-gsfc-nasa-gov/datasets?keywords=merra&page=1&subject=Atmospheric%20Radiation&temporalResolution=1%20hour

2.2.4 Estimation of technological inputs

Estimating the technological parameters is always difficult, since the related values have been showing great progress over the years and are anticipated to change remarkably even soon. On defining these inputs for the model, our core idea was to compile a hypothetical PV/T collector and a PV module, based on the data specifications of real marker collectors/panels that represent systems with very high performance. The advantage of such constructions is that solar collectors/panels with a similar performance are expected to infiltrate slowly during the next decade(s) to the real market, thus the future technological development, that is not foreseen by the current version of the BISE model, might be outweighed with this assumption over the long modelling period.

By evaluating literature and more than 20 hybrid PV/T manufacturers, fixed numbers summarized in Table 6 were selected to represent the hypothesized rooftop PV/T collector used during the simulations. For the "idealized" rooftop PV panel, a concrete prototype, the SunPower-Maxeon6 440[15] product was considered, which is one of the most developed rooftop PV panels nowadays. For this particular PV panel 40-year warranty is provided, which means that the degradation rate of this product is very low. In our case it implies that applying this prototype with constant performance measures over the modelling era until 2060 will not result in major overestimation in the technical potential being calculated.

Table 6. Technology-specific variables used in the BISE model

PV panel	Variable	PV/T panel
monocrystalline Si	Technology	monocrystalline Si
22.8%	η_r – Nominal electric efficiency	21.6% (Triple Solar, 2021[16])
–0.29%/°C	β_p – Nominal temperature coefficient	–0.34%/°C (DualSun, 2021[17])
440 W	P_{max} – Nominal power	375 W (DualSun, 2021)
20%	L_{miscel} – Miscellaneous losses	20%
–	m – Flow rate of fluid	0.027 (Triple Solar, 2021)

2.2.5 Scenarios of the BISE model

In order to analyse the impact of different theoretical considerations on the rooftop solar energy production, two scenarios were implemented into the BISE model (Table 7). Both scenarios were

[15] https://sunpower.maxeon.com/int/solar-panel-products/maxeon-solar-panels
[16] TripleSun (2021). Product information for heat pump panels. https://triplesolar.eu/wp-content/uploads/2020/06/Product-information-Triple-Solar-heat-pump-panels-2020.pdf
[17] DualSun (2021). Technical description of SPRING 375 Shingle Black model. https://my.dualsun.com/wp-content/uploads/DualSun-FR-Fiche-technique-SPRING-375-Shingle-Black.pdf

aimed at assessing the change in the technical potential through distinct installation rates and technological progress of PV/T collectors.

Table 7. Brief summary of the scenarios used in the model

Scenario	**Focus regions**	**Nr. of subcases**	**Initial value of U_F**	**Peak value of U_F**	**Temporal change in U_F**	**Change in energy yield by techn. prog.**
Baseline	All BISE regions	1	Theoretical maximum	Theoretical maximum	No change	No
Rapid technological progress	All BISE regions	1	10%	Theoretical maximum	Exponential	Yes

In the "Baseline" case, it is assumed that about one-third (depending on the regional U_F) of the total rooftop area is the area suitable for installing solar systems. In the "alternative" scenario (i.e., the "Rapid technological progress" scenario), on the other hand, it is hypothesized that from a low level (10%) of the U_F (translating and extending the information that about 90% of the European roofs are uncovered[18] to all regions) the utilization grows in an exponential pace until reaching its theoretical maximum. After this modelling year, the U_F was set to be equal to that of in the "Baseline" case (Table 7).

An additional important distinction of the two scenarios is the assumed design of the PV/T collector prototype. In the "Baseline" scenario, although a high-efficiency rooftop PV/T collector is considered (please refer to Table 6), it is very likely that the energy yield of future PV/T collectors could be much higher relative to the current possibilities. As Mellor et al. (2018) reported, to improve the efficiency of hybrid solar systems, there is a need to limit the convective, radiative heat and power losses during episodes with high cell and inlet fluid temperature. After comparing PV, T and PV/T technologies with regard to economic return, carbon saving and energy production potential, they found that PV/T collectors with Argon-filed cavity between their glazing layer and PV cover glass as well as with low-e coatings can be financially competitive against "conventional" PV and thermal systems in the near future and can produce about 3 times more energy as the "standard" PV/Ts (Table 7).

By assuming that such PV/T collectors as described Mellor et al. (2018) become widely used in the future in the solar rooftop market, the modelled regional thermal energy production potential simulated by the "Baseline" case is increased gradually in the "Rapid technological progress" scenario to represent the infiltration of this technology (and other new technologies) to the daily practice. Precisely, after 5-year of the modelling period, the technology is prescribed to appear first in Europe (in the Western and Eastern Europe regions), followed by a 10-year exponential growth in the energy production from the "reference" level to its 300% (3-fold more thermal energy yield annually). To include deviations in the spread of this technology, the corresponding growth is introduced slightly later for the other BISE regions: from 2030 in North America, Centrally Planned Asia and Pacific OECD and from 2037 in Africa, Former Soviet Union, Latin America, Middle East and Africa, Pacific Asia and South Asia. In each region, the growth is set to stop after the 10-year period. In summary, therefore,

[18] https://www.gensed.org/assets/attachments/dosyalar/EU-Market-Outlook-2020-2024-SolarPowerEurope.pdf

the “Rapid technological progress” scenario was not designed to inform about the technical potential of rooftop PV/T technology, it rather mimics a possibility when both the installation and performance of the hybrid systems show an explosion in the near future.

2.2.6 Further modelling steps

Once the different inputs are prepared, they are fed into the algorithm core of the model, which includes a set of mathematical and physical expressions to convert inputs to the desired rooftop PV/T and PV technical potential. All equations applied in the conversion are described in detail in Molnár et al. (2022). The BISE model performs the calculation on a grid system covering the entire globe. Then the grid-based results can be aggregated and disaggregated in the desired way employing the distribution of rooftops across the World. In Section 3., the modelling results are presented, with special focus on segregations for different regions and building types. Besides the results of “Baseline” (default) case, the technical potential given by the “Rapid technological progress” scenario is also analysed to explore what could be the theoretical maximum of the rooftop-related solar thermal and electric energy production. Please note that in the following parts, only the BISE results for the hybrid rooftop PV/T potential is shown, the rooftop PV-related outcomes are not presented now. For detailed PV-related simulations, please refer to Molnár et al. (2023).

3. Results and Discussion: Analyzing energy demand for different climate zones and urban areas of the regions across the globe

3.1 Global and regional distribution of projected annual floor area

The global total floor area is projected to increase from 287 billion m^2 to 508 billion m^2 between 2022 and 2060, with a corresponding relative annual growth rate of 2% (Table 8). It can be concluded that, however, some of the estimated regional changes could be very different relative to the global one. Among the regions, the lowest growth rates occur in Pacific OECD, Western Europe, Eastern Europe and North America, generally in the developed regions. In the emerging economies, on the other hand, the relative elevations can be as high as 2.3% (Middle East and Africa: 2.8%, Pacific Asia: 2.7%, Africa: 2.3%, Latin America: 2.3%). Despite the significant predicted expansion of the building stock in these areas, the largest simulated total floor area values in 2060 are found for Centrally Planned Asia (2022: 85.6 billion m^2, 2060: 133.1 billion m^2), South Asia (2022: 47.8 billion m^2, 2060: 94.0 billion m^2) and North America (2022: 37.8 billion m^2, 2060: 53.5 billion m^2), which can be explained by the initially high reference (2022) levels of these areas. For more detailed analysis on the floor area projections, please refer to Ürge-Vorsatz et al. (2023b).

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Table 8. Regional values of projected floor space (in certain years; billion m^2) and its annual relative growth (between 2022 and 2060; %/year) used by the HEB model

Region	2022	2035	2050	2060	Annual growth
Africa	17.8	25.4	35.0	41.1	2.3
Centrally Planned Asia	85.6	106.2	122.7	133.1	1.6
Eastern Europe	4.5	5.2	5.7	6.0	1.3
Former Soviet Union	12.0	13.9	16.3	18.2	1.5
Latin America	17.5	25.3	34.5	40.5	2.3
Middle East and Africa	12.0	18.6	27.3	33.7	2.8
North America	37.8	42.4	48.6	53.5	1.4
Pacific OECD	8.1	8.7	9.5	10.1	1.3
Pacific Asia	15.0	23.3	33.7	41.0	2.7
South Asia	47.8	72.1	91.0	94.0	2.0
Western Europe	28.6	31.4	34.8	37.1	1.3
World	**286.7**	**372.4**	**459.2**	**508.2**	**2.0**

3.2 Global and regional distribution of annual energy demand

In 2022 the aggregated building energy demand for space heating, cooling and hot water is modelled to be 28 PWh globally (Figure 10). As the different HEB scenarios anticipate highly diverse building stock in terms of energy efficiency, the projected demand varies between 7.3 and 50.3 PWh by 2060. In the Frozen efficiency scenario, for example, a growth of 80% is found, whereas there is a decline of 74% in the Net Zero scenario over the modeling period (Figure 10).

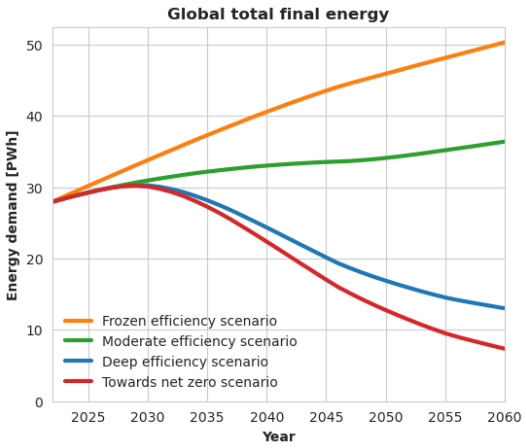


Figure 10. Global total final energy demand of buildings simulated by different HEB scenarios for the 2022–2060 period

Regionally, the predicted energy demand has similar tendencies to that of global figure (Figure 11). By considering the lowest energy performance of building (i.e., the Frozen scenario), the aggregated value shows the largest change in South Asia (231%), Middle East and Africa (171%), Centrally Planned Asia (145%) and Pacific Asia (143%) between 2022 and 2060. Slightly lower increases occur in Latin America (95%) and Africa (83%), while the shift is the least pronounced in Western Europe (12%), Eastern Europe (11%) and Pacific OECD (–1%). The Moderate efficiency scenario, which incorporates

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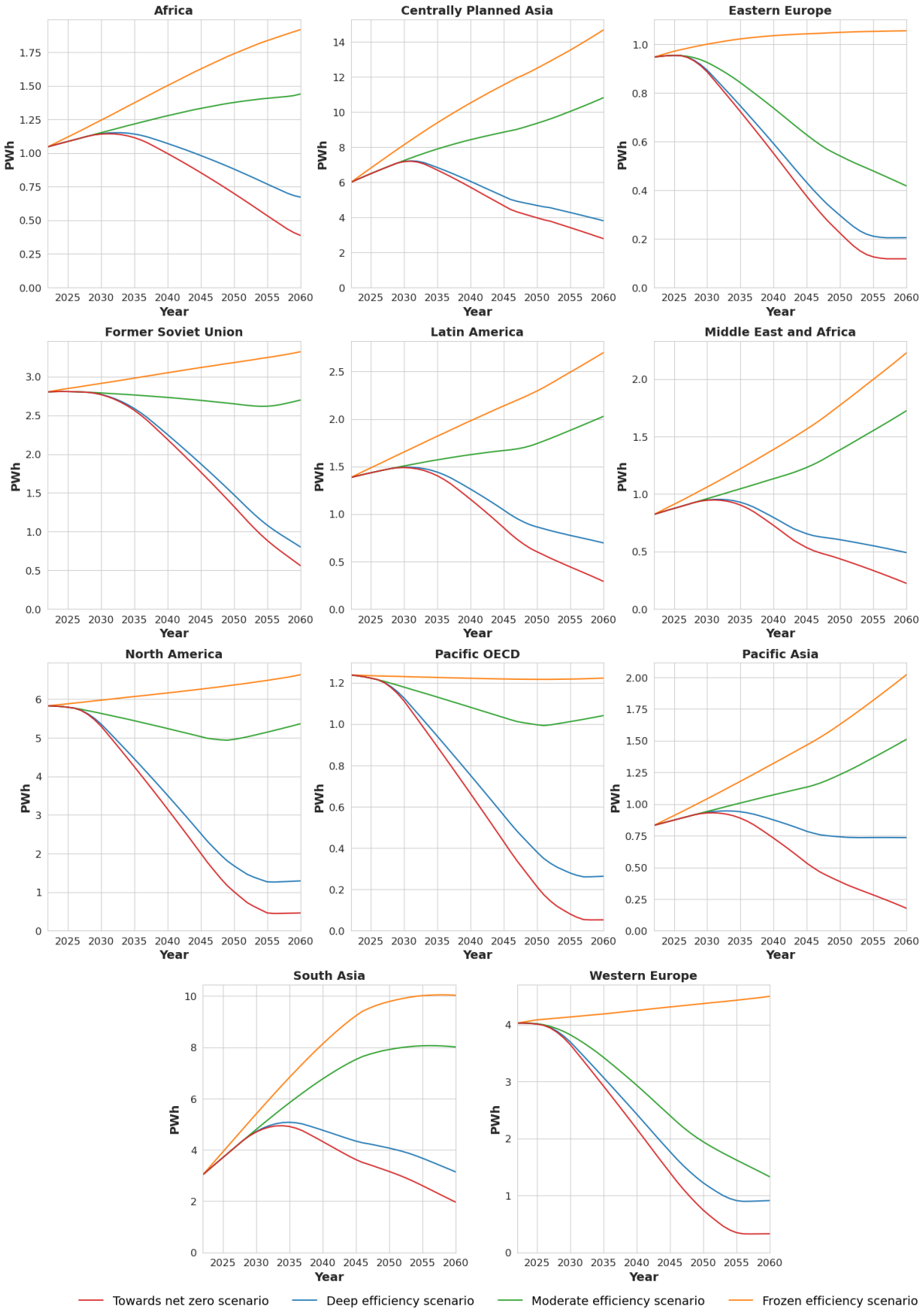


Figure 11. Regional total final energy demand of buildings simulated by different HEB scenarios for the 2022–2060 period

the present efficiency policies, can be characterized by a weaker, but still significant growth in many regions, as compared to the Frozen case. The largest rise in the demand may take place in South Asia (164%), Middle East and Africa (110%) and Centrally Planned Asia (82%). Conversely, the related shifts may be the lowest, showing strong negative values (decrease), in Pacific OECD (–16%), Eastern Europe (–56%) and Western Europe (–67%). In the Deep Efficiency scenario, the demand shows a remarkable decrease in the vast majority of the regions, with relative changes from –12% (Pacific Asia) to –79% (Pacific OECD).

Once the energy performance of buildings is elevated by the onsite energy supply of rooftop photovoltaics, the demand could be further reduced in many regions. In regions, where the climate is the most favorable for PV power production (e.g., South Asia) and the roof availability is high, the projected demand of the Net Zero scenario indicates significant drop to the level of the Deep scenario. In this case, consequently, all regional values have a substantial negative trend, with relative changes even below –90% in three regions (Western Europe: –92%; North America: –92% and Pacific OECD: –96%) (Figure 11). A major implication of this scenario is that by hypothesizing a highly energy efficient building sector equipped with onsite clean energy providers, the current demand can be lowered to a nearly zero level in many modelled regions.

Examining the total demand by end-uses, more insight is gained on which energy services could be the most dominant during the next decades and in what extent they should be balanced to reach a climate resilient building sector. As Figure 12 illustrates, the space heating is estimated to have the largest split (59%) in the total building-related demand on global scale in 2022. Space cooling and hot water demand is simulated to have similar shares with 19% and 22%, respectively. It suggests that the space heating of the global building sector is projected to be 16.6 PWh. Depending on the assumed building performance metrics in the HEB, the modelled heating demand could show a shift between –86% (2.6% – Net Zero scenario) and 51% (13.9% – Frozen Efficiency scenario) globally by 2060 (by 2030). These results, therefore, highlight that despite the general increases of the heating demand in all scenarios during the first years of the analyzed period, introducing advanced buildings to the stock and employing onsite renewable energy could lead to much lower demand for heating by 2060.

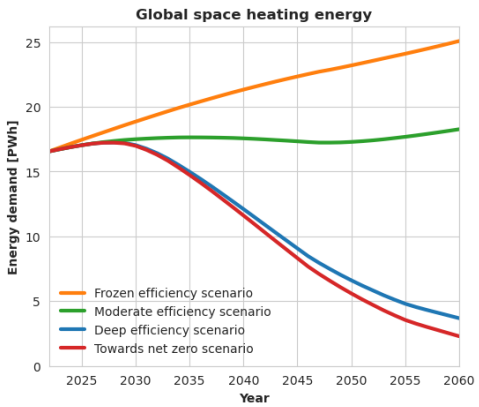


Figure 12. Global space heating demand of buildings simulated by different HEB scenarios for the 2022–2060 period

The global building-associated space cooling has an estimated value of 5.3 PWh in 2022 and its scenario-dependent values are projected to alter by –51 (Net Zero: 2.6 PWh), 1 (Deep: 5.3 PWh), 118 (Moderate: 11.6 PWh) and 163% (Frozen: 14.0 PWh) by 2060 according to the HEB scenarios (Figure 13). Both the relative and absolute values emphasize that the cooling demand of the global building sector might be lowered less efficiently than that of space heating. It stems from two assumptions

used by the HEB model. Firstly and most importantly, the energy intensity inputs for space cooling have higher base values and are considered to very less between building the advanced and non-advanced buildings. Secondly, the rooftop PV production in a given region is initially used to balance space the heating, and then only the remaining amount (if any) is applied to satisfy demand from other end-uses (incl. the cooling).

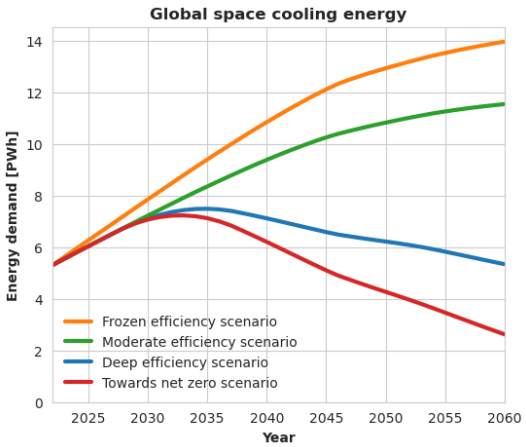


Figure 13. Global space cooling demand of buildings simulated by different HEB scenarios for the 2022–2060 period

In regional sense, space heating and cooling often exist simultaneously over an annual time scale, therefore their regional values are now presented in a combined form. The largest aggregated space heating and cooling demands in 2022 are revealed for Centrally Planned Asia (5 PWh), North America (4.2 PWh) and Western Europe (2.8 PWh), whereas the lowest ones for Africa (0.9 PWh), Middle East and Africa (0.7 PWh), South Asia (0.7 PWh) and Eastern Europe (0.6 PWh) (Figure 14). Analyzing the end-uses separately, the predicted demand is dominated by space cooling only in Pacific Asia (87% of the total demand), South Asia (84%) and Africa (66%). In the other regions, the demand associated with space heating has much larger values, especially in the Former Soviet Union, Western Europe and Eastern Europe. These modelled differences are driven, on the one hand, by the amount of floor area needed to be heated/cooled and, on the other hand, by different inputs for their energy intensities. Naturally, the climate of given regions is also a crucial factor, which impacts the energy needs through the energy intensity.

By 2060, the regional heating and cooling demand is expected to decrease or stagnate in Pacific OECD, and Western Europe, irrespective to the selected scenario (Figure 14). In fact, the simulation of Net Zero calculates a nearly zero demand for these regions. In the other regions, the outcome could be much more uncertain, depending strongly on the future efficiency of the building sector. Among the Frozen and Net Zero (i.e., the most pessimistic and optimistic) scenarios, the difference for the aggregated demand might be the largest in Centrally Planned Asia (9.7 PWh; 193% of the 2022 value) South Asia (7 PWh; 285% of the 2022 value) and North America (4.4 PWh; 105% of the 2022 value). It comes from the findings of the HEB model that the Net Zero scenario emphasizes a large potential to achieve significant demand curtailment, with a relative change of about –80% relative to the 2022 level (worst cases in: South Asia – 26% reduction; Africa – 63%). Generally, of the two energy services, more potential to reduce the energy needs is modelled for the space heating, except for the regions of Africa, Middle East and Asia, Latin America, Pacific Asia and South Asia.

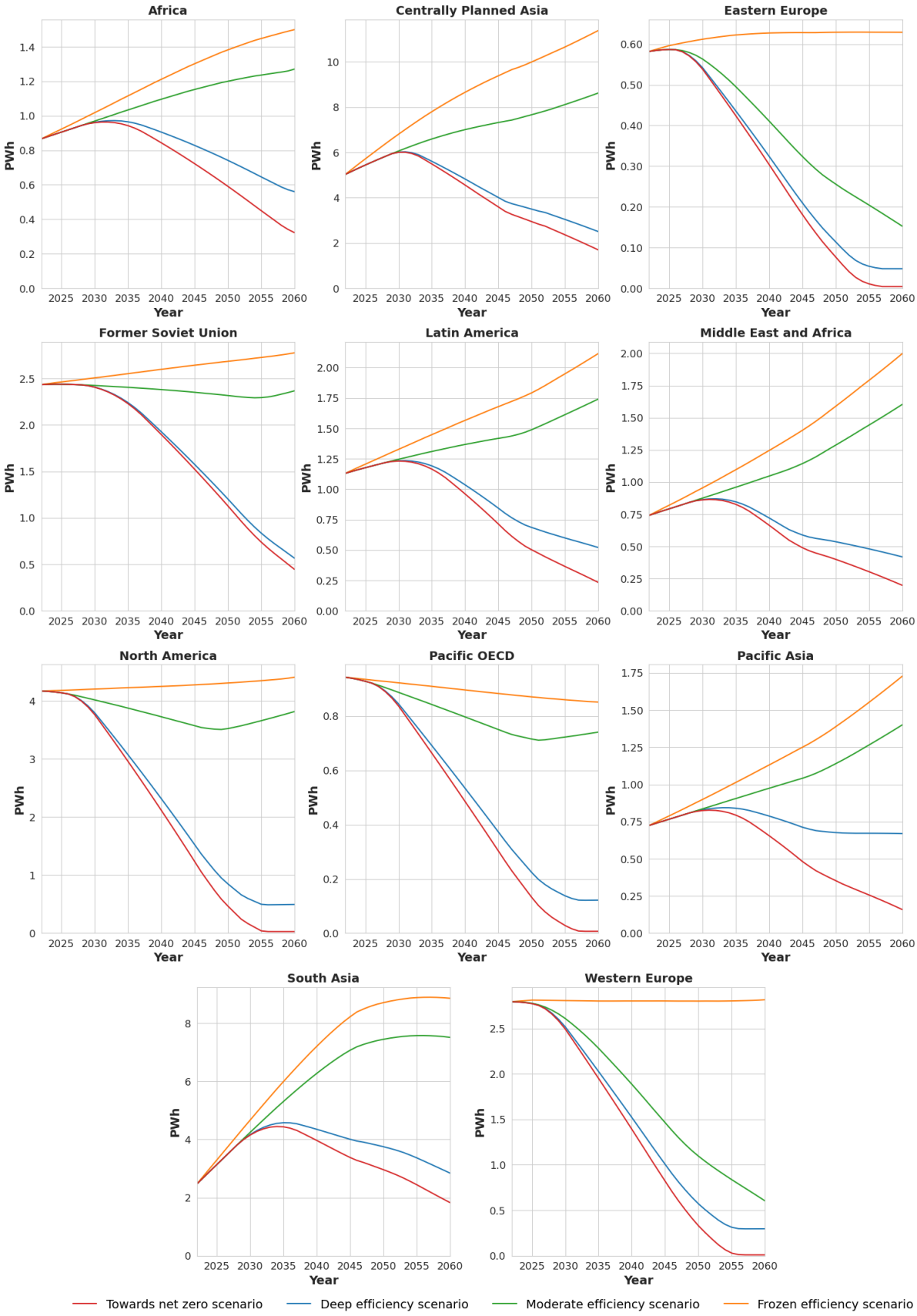


Figure 14. Regionally aggreagted space heating and cooling demand of buildings simulated by different HEB scenarios for the 2022–2060 period

The global energy demand for hot water production is found to be 6.1 PWh in 2022 (Figure 15). In contrast with the heating and cooling need, the future values of this type of energy usage are modelled to be less dependent on the policies set in the scenarios. Precisely, the reduction potential is not so high in the Net Zero (–60%) and Deep (–35%) cases, while the undesired rises are not so dominant in the Moderate (8%) and Frozen (85%) ones. Thus, the corresponding global demand for 2060 varies between 2.4 (Net Zero) and 11.3 PWh (Frozen efficiency) in the scenarios. If the change in the global share of this energy service is contrasted, it can be observed that it remains to be around the 2022 level in the Frozen and Moderate scenarios, meanwhile it slightly increases in the Net Zero and Deep scenarios during the analysis period. This modeling result also underlies that increasing the energy efficiency measures of buildings might have lower impact on demand reduction for hot water production than space heating globally. On the other hand, slower (or negligible) improvement of energy performance of buildings accompanied with an expanding building stock might not lead to as much growth in the demand as the other end-uses analyzed by the HEB model.

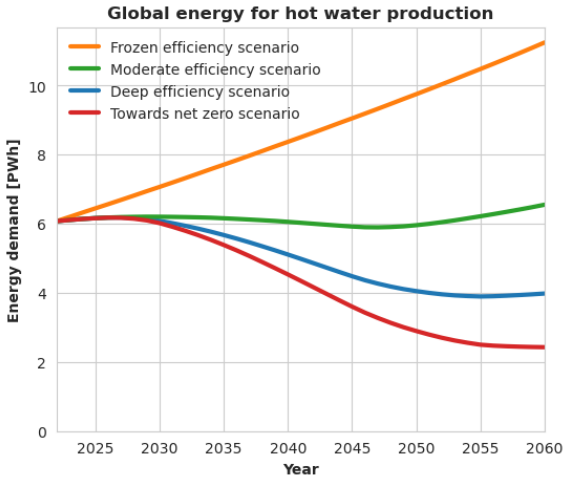


Figure 15. Global demand for hot water production of buildings simulated by different HEB scenarios for the 2022–2060 period

Regionally, the largest estimated energy demand for hot water production in 2022 occurs in North America (1.7 PWh), Western Europe (1.2 PWh), Centrally Planned Asia (1 PWh) and South Asia (0.6 PWh) (Figure 16). By the end of the modeling period, the most pronounced HWP demands are also projected for these countries in each experiment, while the least values are found in Middle East and Africa, Africa and Pacific Asia. If no improvements in the energy performance of buildings occur (i.e., Frozen scenario) in the future, the demand for HWP could go up by 17% (Eastern Europe) – 241% (Centrally Planned Asia). In the meantime, even with the best hypothesized efficiency, the corresponding reduction potential could be maximum around –80% (–84%: Pacific OECD, –83%: Pacific Asia, –76%: Latin America). Consequently, a complete reduction of HWP demand looks to be unlikely in any region, at least on an annual time scale, by 2060.

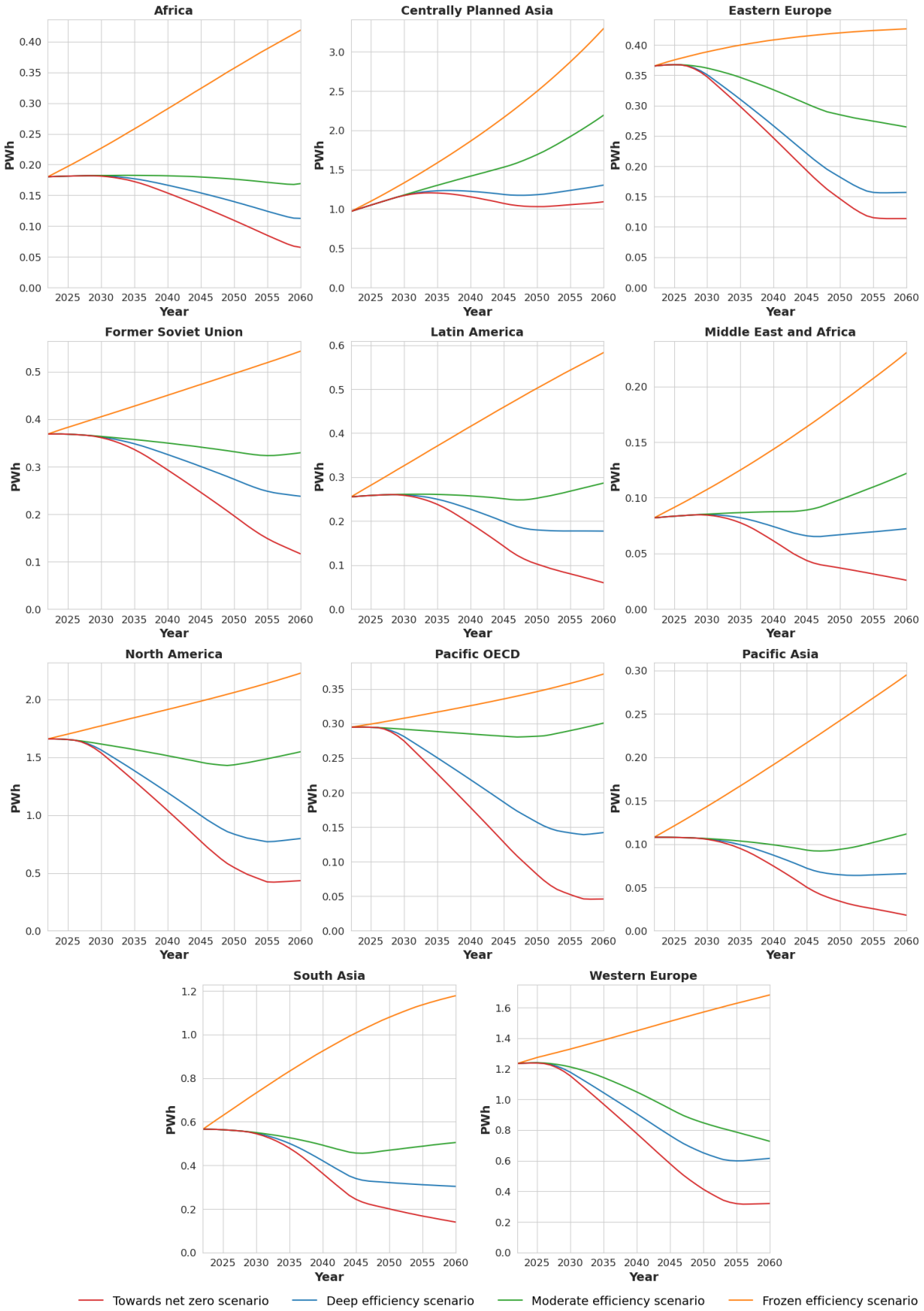


Figure 16. Regional demand for hot water production of buildings simulated by different HEB scenarios for the 2022–2060 period

Since the projected floor space area depicts many dissimilarities between residential, tertiary buildings and slums (Figure 17), it is important to evaluate how the related demand of different evolve over the analysis period. The aggregated global energy demand is modelled to be 18.2, 9.6 PWh and 0.2 PWh for residential, commercial/public and slums in 2022, representing shares of 65, 34 and 1%, respectively. As it is concluded earlier, the floor area of tertiary buildings and slums is projected to grow more than the residential floor space, hence the global values of the building-related energy demand show the largest changes for these building categories. Discussing the different scenarios separately, the global energy demand is characterized by prominent year-to-year increases (residential: 1%/year, tertiary: 3.9%/year), especially for the slums (4.2%/year) in the Frozen Efficiency scenarios. Analogously, the Moderate Efficiency scenario yields rising trend for the tertiary (2.2%/year) and slum (2.2%/year) types, but minor decline can be identified for residential ones (<0.1%/year). Although for slums, the same tendencies as in the Moderate case are found both in the Deep Efficiency and Net Zero scenario due to methodological considerations, energy demand in residential and commercial/public buildings are estimated to decrease by these scenarios. Either the Deep or the Net Zero scenario anticipates better annual reductions (Deep: –1.6%/year, Net Zero: –2.1%/year) for residential buildings until 2060. These trends are –1%/year in the Deep and –1.6%/year in the Net Zero scenario. Therefore, owe to the more favorable energy performance metrics and despite the larger floor area of residential buildings, the corresponding energy demand is expected to have the same magnitude than that of commercial/public buildings in each scenario by 2060 (e.g., Frozen – residential, tertiary: 18-18 PWh, Net Zero – residential, tertiary: 3.4-3.6 PWh). Because of the assumption and tendencies presented above, the relevance of tertiary buildings might grow towards 2060, in terms of the demand management.

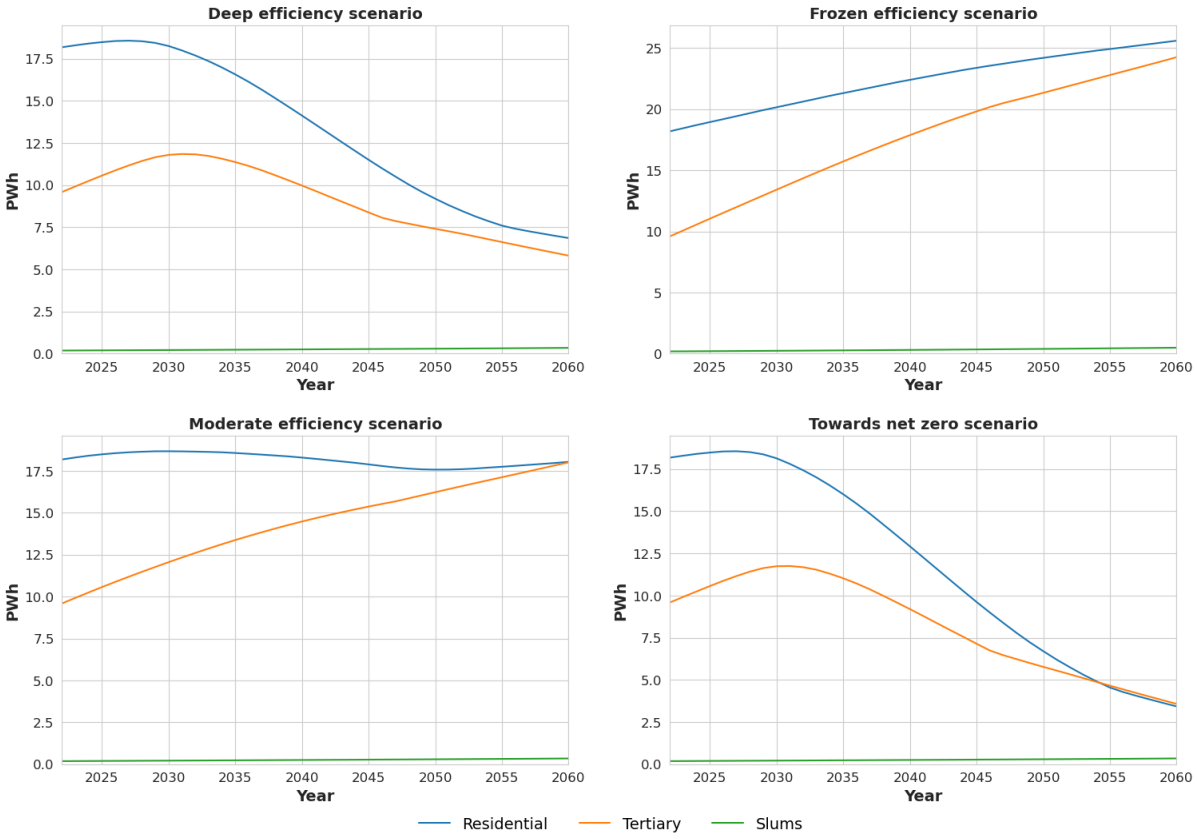


Figure 17. Global total final energy demand of residential and tertiary buildings as well as slums simulated by different HEB scenarios for the 2022–2060 period

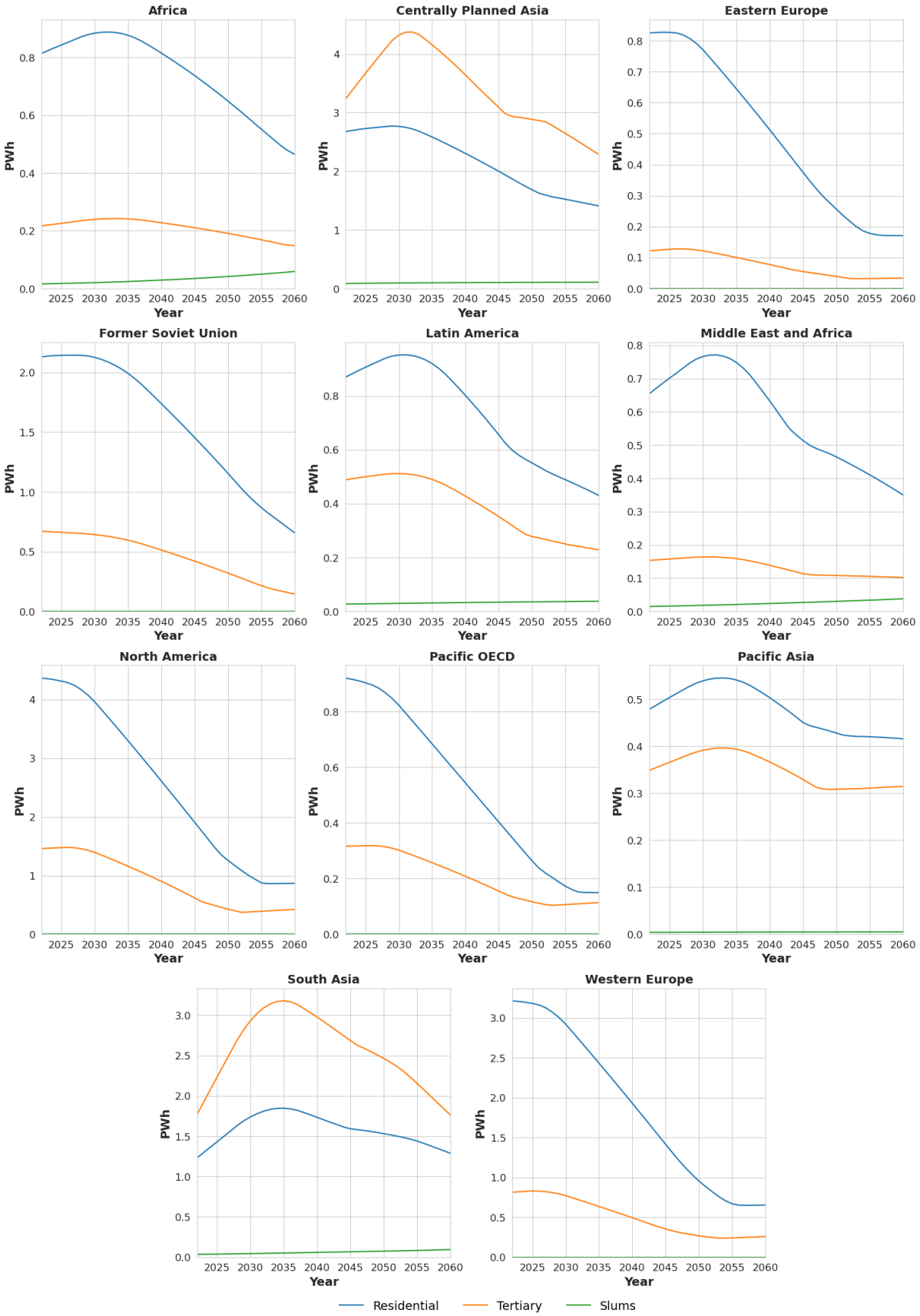


Figure 18. Global total final energy demand of residential and tertiary buildings as well as slums simulated by the Deep Efficiency scneario for the 2022–2060 period

Regionally, the aggregated energy demand for slums is projected to increase mostly in Africa and South Asia over the 39-year investigation era, irrespective to the scenario (Figure 18). The shift in the residential energy need could be greatest in Middle East and Africa, South Asia and Pacific Asia, driven primarily by the population-related residential floor area estimation of the HEB. In the meantime, decreases with different magnitudes appear in all scenarios for North America and Pacific OECD. In these regions, demand reductions below –80% could be achieved for residential buildings, based on the Deep and Net Zero scenarios. For the tertiary buildings, the modelled changes are particularly substantial in the Frozen and Moderate cases for Centrally Planned Asia (242 and 177%), South Asia (204 and 155%) and Pacific Asia (165 and 100%). On the other hand, the lowest reduction in the tertiary energy demand is estimated exactly for these regions by the Deep and Net Zero scenarios between 2022 and 2060. Due to the smallest changes in the predicted tertiary floor area and major improvements in energy efficiency, the reduction potential for tertiary demand could be significant in North America (Deep: –71%, Net Zero: –88%), Western Europe (Deep: –68%, Net Zero: –93%) and Pacific OECD (Deep: –64%, Net Zero: –94%). In summary, by discussing absolute values, the residential energy demand by the end of the modelling period is modelled to be the most significant in South Asia (Frozen: 4.5 PWh, Moderate: 3.4 PWh, Deep: 1.3 PWh, Net Zero: 0.6 PWh) and North America (Frozen: 4.2 PWh, Moderate: 3.4 PWh, Deep: 0.9 PWh, Net Zero: 0.3 PWh), while it is the lowest in Pacific OECD (Frozen: 0.7 PWh, Moderate: 0.6 PWh, Deep: 0.1 PWh, Net Zero: 0.03 PWh) and Eastern Europe (Frozen: 0.9 PWh, Moderate: 0.4 PWh, Deep: 0.2 PWh, Net Zero: 0.01 PWh). For the tertiary energy need, the greatest values are found in Centrally Planned Asia (Frozen: 11.1 PWh, Moderate: 8 PWh, Deep: 2.3 PWh, Net Zero: 1.6 PWh) and South Asia (Frozen: 5.4 PWh, Moderate: 4.5 PWh, Deep: 1.8 PWh, Net Zero: 1.3 PWh), whereas the least simulated demand occurs in Middle East and Africa (Frozen: 0.4 PWh, Moderate: 0.3 PWh, Deep: 0.1 PWh, Net Zero: 0.03 PWh) and Eastern Europe (Frozen: 0.2 PWh, Moderate: 0.05 PWh, Deep: 0.03 PWh, Net Zero: 0.01 PWh).

3.3 Hourly distribution of energy demand in different regions

The building-related energy demand for space heating, cooling and hot water production depends strongly on such environmental factors as air temperature, solar radiation, humidity and wind speed. It implies that in regions with major seasonality in their climate, the intra-annual variation of the above energy services could be substantial.

Space heating, as the most relevant demand source, show its maxima in January in regions with most of their areas in the northern hemisphere (e.g., Centrally Planned Asia, Former Soviet Union and North America), while in other regions, maxima occur in July (e.g., Africa and Latin America) (Figure 19) over the base year of the simulation time frame. In these periods, the largest heating needs emerge in Centrally Planned Asia, North America, Western Europe and Former Soviet Union. The minima, on the other hand, distribute to more months than the maxima. The lowest values are found in January for Africa, in February for Latin America, in June for Middle East Africa, in September for Pacific OECD and Pacific Asia and in July for the remaining regions. For Africa and Middle East Africa, no heating need is estimated in the respective months. In summary, space heating is demanded less frequently in Africa (66% of the hours of the year), in Middle East and Africa (70%) and Pacific Asia (78%). In the other regions, heating may be required in more than 90% of the year.

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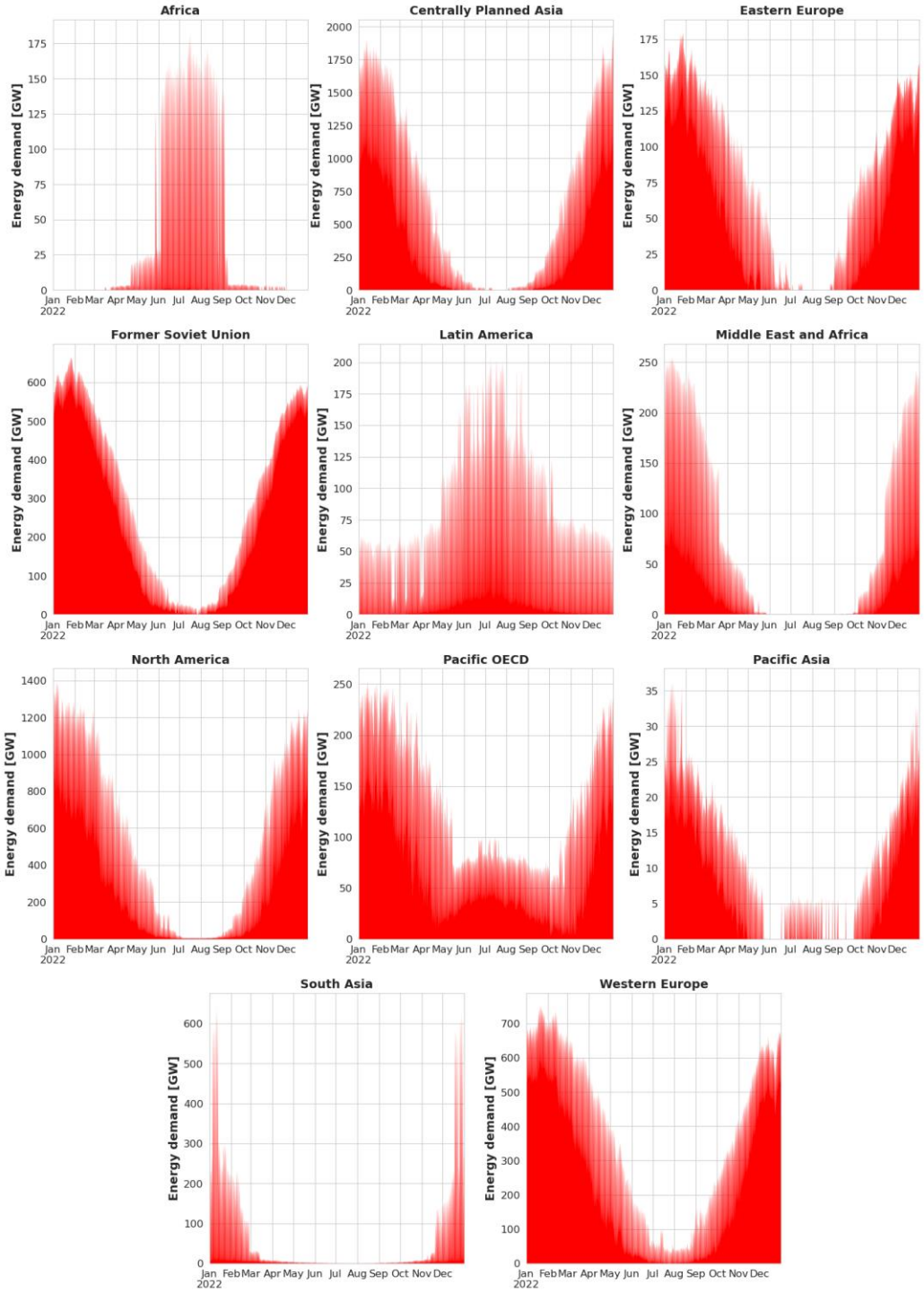


Figure 19. Regional values of hourly space heating demand of buildings simulated for the year 2022

Space cooling is needed especially during warm periods, hence the related demand indicates reverse distribution relative to the heating (Figure 20). The maxima are predicted in March for Africa, in May for Pacific Asia and South Asia, in July for Centrally Planned Asia, Former Soviet Union, Middle East and Africa, North America and Western Europe, in August for Eastern Europe and Pacific OECD and in October for Latin America. The maxima are projected for South Asia, North America, Centrally Planned Asia and Latin America. During the peak winter months (i.e., December-January: northern hemisphere, June-July: southern hemisphere), space cooling demand has its minima, with negligible need in Eastern Europe, Former Soviet Union, Western Europe. Using the coefficient of variance (by definition,

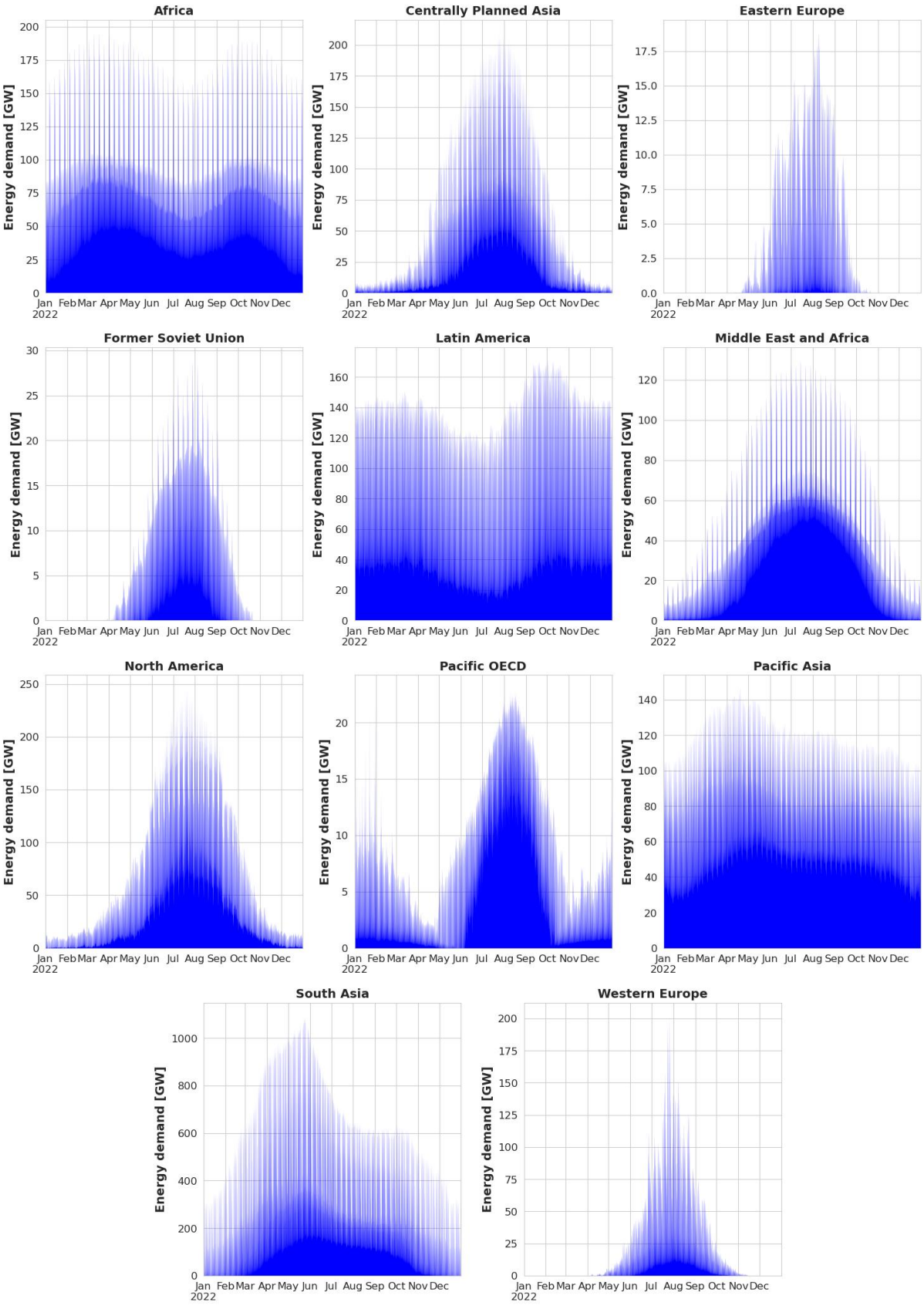


Figure 20. Regional values of hourly space cooling demand of buildings simulated for the year 2022

expresses the dispersion of the distribution of a given variable) as a statistic measure of variability, the lowest coefficient is computed for Pacific Asia (12%), Africa (13%) and Latin America (14%). It can be interpreted as that if cooling demand occurs, the corresponding monthly magnitudes are very similar during this period. In the meantime, much higher variability is found for the European regions and for North America. The lowest occurrence of cooling need is simulated for regions with high fraction of areas over the 40° latitude in the north and south and with less areas in the lower latitudes. To these regions belongs Eastern Europe (41% of the hours of the year might occur cooling need), Former Soviet Union (44%) and Western Europe (56%). For the other regions, cooling need could emerge, with even small magnitudes, over the entire year.

Among the inspected energy services, the need for hot water production has the most balanced intra-annual distribution based on Figure 21. Since this demand category often coexists with space heating, their hourly distributions depict many similarities during a typical year. First, the maxima befall typically in the cold period. It is noteworthy, however, that while the largest values of the space heating demand occur in January (July) in regions located in the northern (southern) hemisphere, the maxima of HWP demand might be experienced one-two months later. For example, the maxima typically are observed in March (e.g., Eastern Europe, North America, Pacific OECD) and October (e.g., Africa and Pacific Asia) (Figure 21). This phenomenon is the consequence of an important assumption of the HEB that the HWP demand is partly the function of the mains temperature. Given that the water pipes are located under the ground that is a medium transfer the heat absorbed from the atmosphere with a certain delay (i.e., high heat capacity), there could be a lag between the change of air and mains temperature. For the same reason, the minima of the related demand is estimated mostly for the months of February (e.g., Africa and Latin America), June (e.g., Pacific Asia and South Asia) and September (e.g., Western Europe and North America). Nonetheless, the difference between the (monthly) minima and maxima of the demand is much slighter as compared to other energy services in the HEB. This balanced intra-annual behavior is well demonstrated by the coefficient of variance again that has an estimated regional range from 4–7% (e.g., Latin America, Africa, Pacific Asia and Pacific OECD) to 20–25% (e.g., South Asia and Middle East and Africa). In regional aggregation, the need for HWP could emerge over the entire year in most of the regions.

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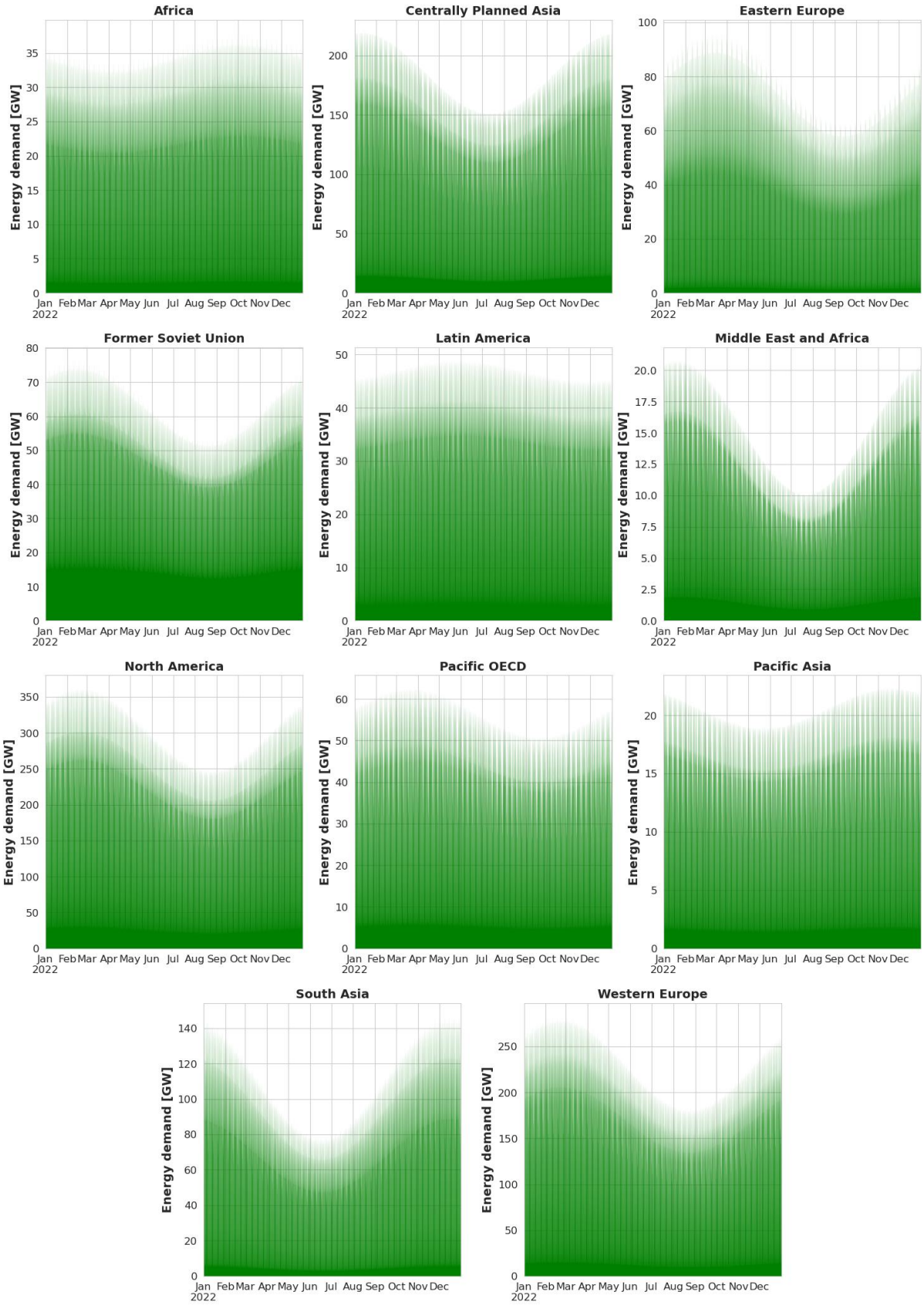


Figure 21. Regional values of hourly demand for hot water production of buildings simulated for the year 2022

Due to methodological considerations (i.e., fixed temperature profiles and occupancy schedules), the temporal distribution of the analyzed demands remains the same over the modeling period, although

the annual energy that is shared over a year could alter significantly. Since the demand is anticipated to generally increase in the Frozen and Moderate scenarios, the difference between the maxima and minima during a certain time frame (e.g., day, week, month and season) could be larger in absolute sense (Figure 22). In other words, if the demand follows these scenarios, the temporal and presumably the spatial variability of its absolute values could be larger for each end-use type. It could be especially true for the less balanced space heating and cooling. However, the HEB model does not take the effects of climate change into account, the expected temperature change in the future could amplify this mechanism. To demonstrate it more in detail, we compare the hourly values of space heating demand given by the Frozen scenario by 2022, 2030 and 2060 as the example of Latin America. The absolute annual demand ranges (i.e., the difference between the maximum and minimum) are 185 (in 2022) and 339 GW (in 2060) (about 2-fold difference in favor of 2060 value). On the other hand, the variability could be much lower once the Deep and Net Zero scenarios are followed. Repeating the previous experiment for the Deep case (Figure 22), the related range would be much smaller, 185 (in 2022) and 57 GW (in 2060) (about 3-fold difference in favor of 2022 value).

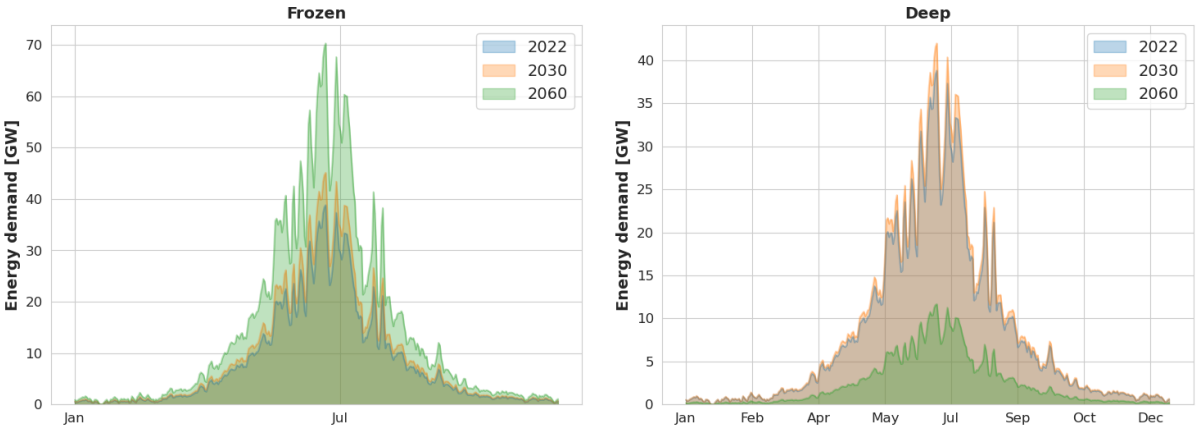


Figure 22. Hourly space heating demand in Latin America given by the Frozen and Deep scenarios for 2022, 2030 and 2060

3.4 Global and regional distribution of annual urban energy demand

As a consequence of an urbanization trend in the last decades, by now more than 50% of the Earth's population lives in urban areas, and this ratio is expected to grow further in the future (UN, 2018). It underlines that urban aspects of solving the energy transition and decarbonization of the building sector will be increasingly important. Therefore, it can be interesting to see how the building-related urban energy demand might evolve over the modeling period if different building energy efficiency measures are applied. By 2022, the HEB estimates 69% of the global building-related energy demand for urban areas (20.7 PWh) (Figure 23). This share is higher than 2018 the urban share (55%), which can be explained by that the HEB model assumes lower accessibility to energy services in rural buildings compared to the urban counterpart. This is especially valid for space cooling for which the proportion of urban demand is modelled to 74% (3.6 PWh). The corresponding values for space heating and HWP demand are projected to be slightly smaller, 70 and 63%. Over the 39-year analysis period, the urban demand share for space cooling is expected to rise around 75–81% in the scenarios. Scenarios anticipating least advanced buildings within the stock generally have the larger ratios. The share of urban space heating demand is simulated identically to be 80% each scenario, which yields a higher increase relative to the base year. Yet, the largest increase in the urban share is found for the HWP for which the urban demand has a slice of around 74–77% in its total value. The changes in the

different shares have two implications on urban demand. On the one hand, despite the rapid urbanization in the future, the share of urban space cooling need is anticipated to grow as fast as other energy end-uses as compared to 2022. The urbanization may mostly take place in developing economies, so it can be deciphered that the future access to expensive A/C system in these areas could still be limited. Therefore, the increase in the urban space cooling demand is reduced relative to that of space heating and hot water production. On the other hand, as the scenario-dependent results highlight, the future urban shares might be independent from the efficiency measures, relying rather on the urbanization rate and accessibility to technologies. Nonetheless, the absolute values of urban demand depends strongly on the energy performance of buildings.

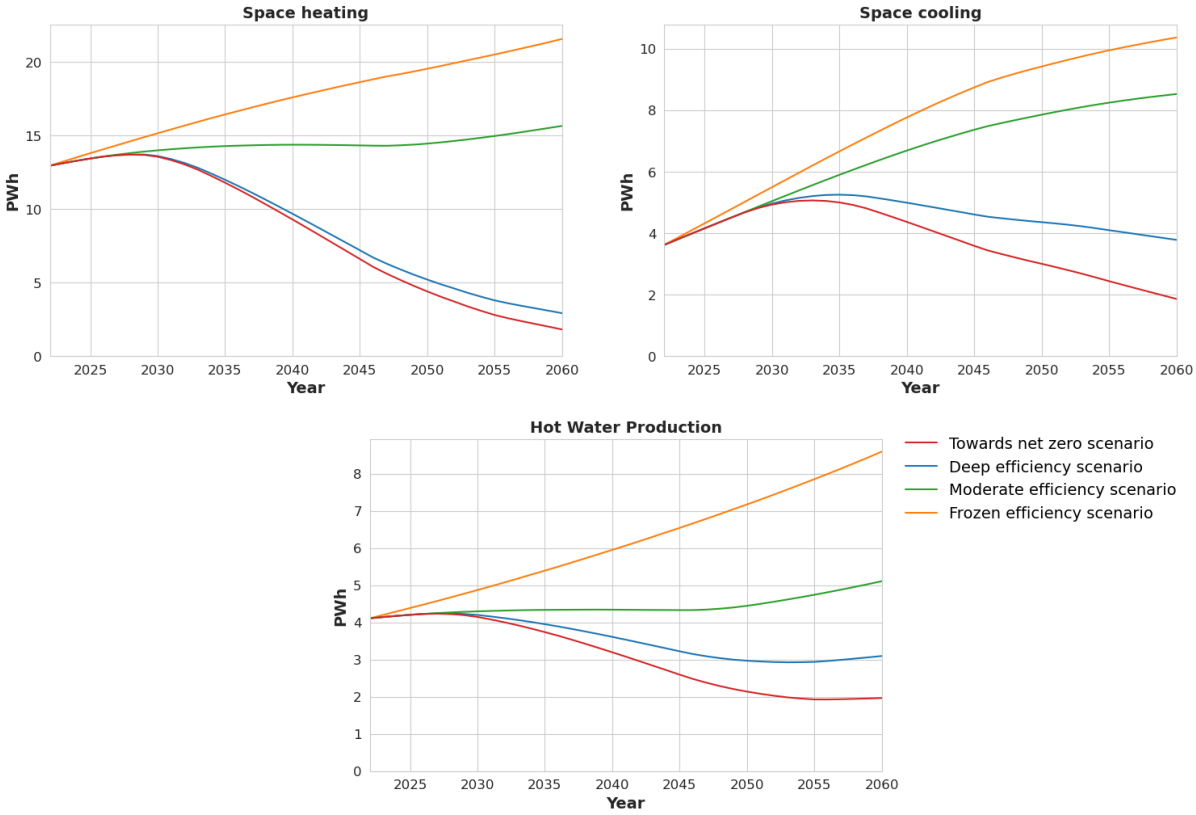


Figure 23. Global energy demand for space heating, cooling and hot water production of urban buildings simulated by different HEB scenarios for the 2022–2060 period

Since regional fractions of urban energy demands change insignificantly between the scenarios, here we only discuss the year-to-year relative shifts of urban energy demand by regions and energy services, based on the Deep Efficiency case. The urban need for space heating is revealed to be the lowest for Africa (32%), Eastern Europe (58%) and Middle East and Africa (60%) (Figure 24). Consequently, Africa is the only region for which the rural space heating demand is predicted to be (much larger) than the urban one. On the opposite edge, there are Pacific OECD (91%), Latin America (83%) and North America (83%) for which the most significant urban demand shares are predicted. For 2060, the corresponding shares show increases in most regions, which is the most substantial in Africa (17%), Eastern Europe (17%), Western Europe (9%) and Middle East and Africa (5%). As a result, the Centrally Planned Asia (with 87% share) could become one of the regions with the most urban demand for space heating, along with Pacific OECD (91%) and North America (88%) by the end of the modeling period. In Africa, however, the total space heating demand is split in equal shares for rural and urban areas by 2060.

In 2022, the urban energy demand for space cooling has the largest simulated shares in the most developed regions, viz. in Pacific OECD (91%), North America (84%), Western Europe (84%) and Eastern Europe (83%) (Figure 24). For these regions, as it is presented in Figure 24, the absolute cooling demand is modelled to decrease in most scenarios, whereas the related urban shares are characterized by minor (around 1–5%) growth. It means that the demand reduction of space cooling being anticipated by the scenarios (with highest magnitudes in the Deep and Net Zero cases) might occur with identical efficiency both in urban and rural buildings. In Centrally Planned Asia, Middle East and Africa and Pacific Asia, where the future location of the most significant changes (demand reduction by the Deep and Net Zero, demand surplus by the Frozen and Moderate cases) in the space cooling are projected for the urban areas (Centrally Planned Asia: 11%, Middle East and Africa: 8%, Pacific Asia: 6%). By 2060, due to their simulated absolute values (Figure 24) and their tendencies presented above, the urban space cooling demand could have the largest regional values in South Asia (Frozen: 5.5 PWh, Moderate: 4.7 PWh, Deep: 1.7 PWh, Net Zero: 1.1 PWh), Pacific Asia (Frozen: 1.3 PWh, Moderate: 1 PWh, Deep: 0.5 PWh, Net Zero: 0.1 PWh) and Latin America (Frozen: 1.2 PWh, Moderate: 1 PWh, Deep: 0.3 PWh, Net Zero: 0.1 PWh).

The urban share of HWP energy demand is simulated to be the highest for the similar developed countries as presented for space cooling (Pacific OECD: 89%, North America: 83%, Western Europe: 77%) (Figure 24). If the absolute values are considered, the largest urban HWP demands are found for North America (1.4 PWh), Western Europe (0.9 PWh), Centrally Planned Asia (0.6 PWh) and Pacific OECD (0.3 PWh). Still following the Deep scenario as a basis, the proportion of urban HWP demand rises between 2022 and 2060, mostly noticeably in Africa (19%), Centrally Planned Asia (18%), Eastern Europe (17%) and South Asia (13%). By combining the base shares and the outlined tendencies, the largest urban demand shares could be in Pacific OECD (92%), North America (89%), Western Europe (87%) and Latin America (85%) by 2060. In Africa and South Asia, the urban need for HWP is estimated to be not exceeding the rural values even by 2060. The absolute urban HWP demand in 2060, therefore, indicates its highest values for Centrally Planned Asia (Frozen: 2.5 PWh, Moderate: 1.7 PWh, Deep: 1.0 PWh, Net Zero: 0.9 PWh), North America (Frozen: 2.0 PWh, Moderate: 1.4 PWh, Deep: 0.7 PWh, Net Zero: 0.4 PWh), Western Europe (Frozen: 1.5 PWh, Moderate: 0.6 PWh, Deep: 0.5 PWh, Net Zero: 0.3 PWh). In the meantime, the lowest projected values occur in Africa (Frozen: 0.2 PWh, Moderate: 0.07 PWh, Deep: 0.05 PWh, Net Zero: 0.03 PWh), Middle East and Africa (Frozen: 0.2 PWh, Moderate: 0.09 PWh, Deep: 0.05 PWh, Net Zero: 0.02 PWh) and Pacific Asia (Frozen: 0.2 PWh, Moderate: 0.08 PWh, Deep: 0.05 PWh, Net Zero: 0.01 PWh).

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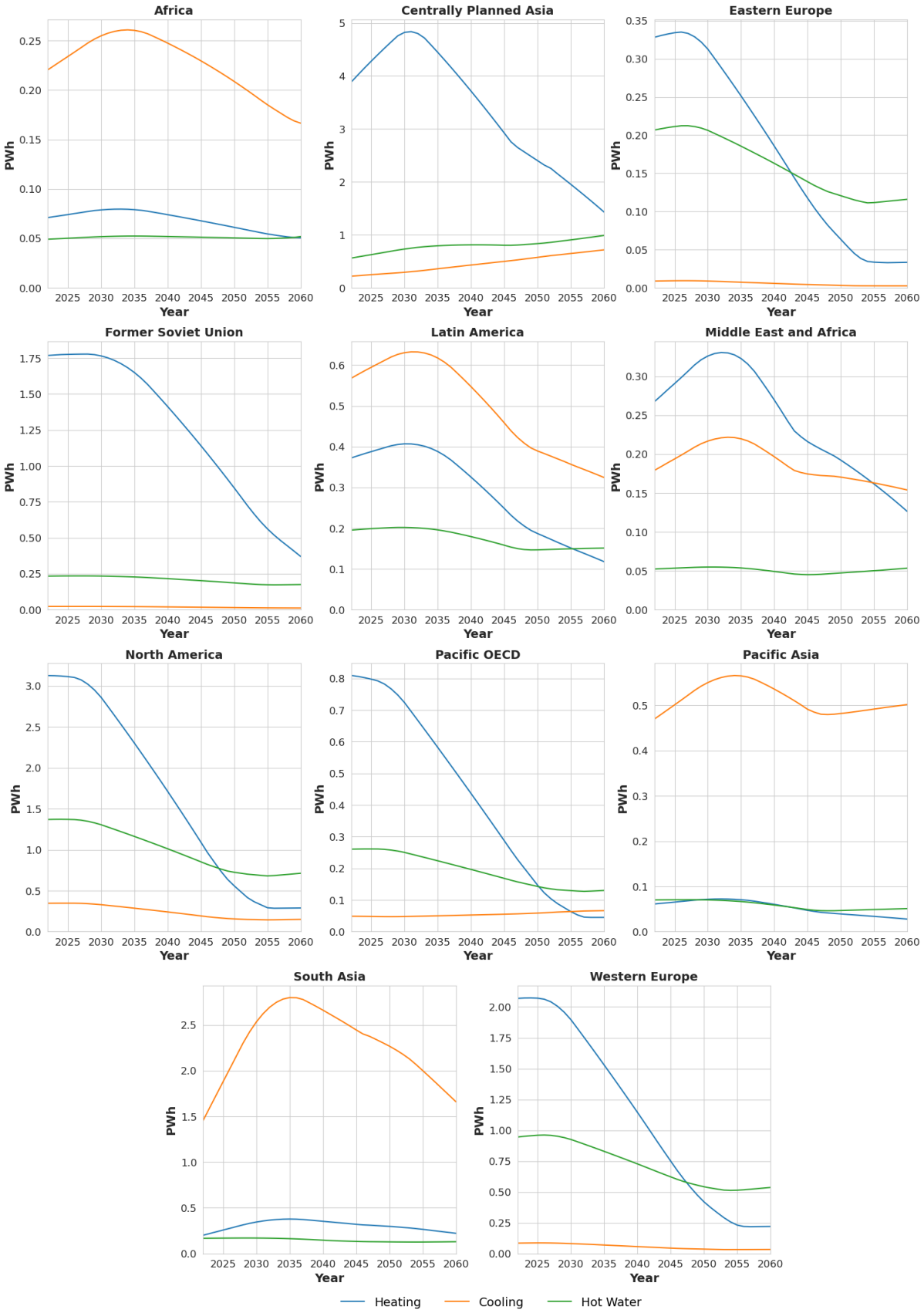


Figure 24. Regional energy demand for space heating, cooling and hot water production of urban buildings simulated by the Deep Efficiency scenario for the 2022–2060 period

If the regional results are decomposed to finer spatial levels, it can be concluded for the urban building-related energy demand that its initial (2022) share is approximated to be largest in the USA and China for space heating (83%), in the EU-27 for space cooling (86%) and in the USA for HWP (Figure 25). On the other hand, India (space heating: 68%, cooling: 71%, HWP: 34%) has always the lowest urban shares in the simulations, even with rural dominance for HPW demand. These shares cover the most significant urban space heating demand in China (3.8 PWh) and the USA (2.8 PWh), space cooling demand in India (1.4 PWh) and the USA (0.3 PWh) as well as HWP demand in the USA (0.6 PWh) and EU-27 (0.6 PWh). As a result of the major expansion of the projected urban building stock in Asia by 2060, the urban demand could change larger over these countries (typically in a range of 5-20%). By 2060, the HEB model simulates the largest urban space heating for China (Frozen: 9.4 PWh, Moderate: 7.1 PWh, Deep: 1.4 PWh, Net Zero: 1.1 PWh) and the USA (Frozen: 3.1 PWh, Moderate: 2.7 PWh, Deep: 0.3 PWh, Net Zero: 0.1 PWh) among the analyzed geographical areas depicted in Figure 25. For space cooling, the related demand could be the most dominant in India (Frozen: 5.3 PWh, Moderate: 4.5 PWh, Deep: 1.6 PWh, Net Zero: 1.0 PWh) and China (Frozen: 0.5 PWh, Moderate: 0.4 PWh, Deep: 0.6 PWh, Net Zero: 0.3 PWh). Finally, the HWP demands are found to be with the peak values in China (Frozen: 1.0 PWh, Moderate: 0.7 PWh, Deep: 0.4 PWh, Net Zero: 0.3 PWh) and the USA (Frozen: 0.9 PWh, Moderate: 0.6 PWh, Deep: 0.3 PWh, Net Zero: 0.1 PWh). If the demand for all analyzed energy end-uses is aggregated, the countries with the most remarkable urban energy demand could be in Asia, concentrating primarily in China (Frozen: 10.9 PWh, Moderate: 8.2 PWh, Deep: 2.5 PWh, Net Zero: 1.8 PWh) and India (Frozen: 6.2 PWh, Moderate: 5.2 PWh, Deep: 1.8 PWh, Net Zero: 1.2 PWh) by 2060. Still, the largest potential to reduce urban energy demand might be taken in the USA and EU-27, based on the results of the Deep (USA: –67%, EU-27: –69%; in the mean of end-uses) and Net Zero (USA: –95%, EU-27: –92%; in the mean of end-uses) scenarios.

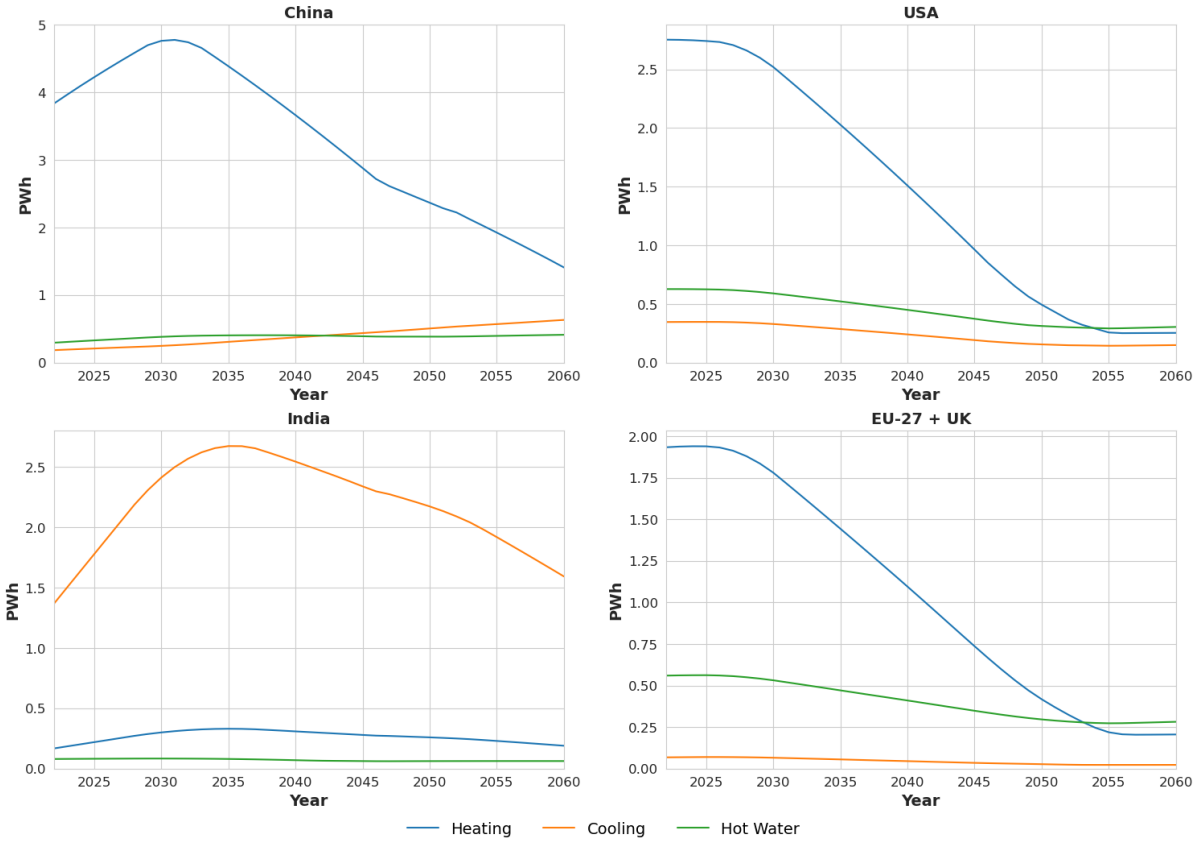


Figure 25. Country-specific and EU-level energy demand for space heating, cooling and hot water production of urban buildings simulated by the Deep Efficiency scenario for the 2022–2060 period

3.5 Regional distribution of annual energy demand in different climate zones

At the discussion of hourly profiles, it is presented that the intra-annual profiles of building energy demand, especially for space heating and cooling, are tightly correlated with climatic parameters recorded in a given region/country. Furthermore, it must be noted again that not only the variability of the profiles, but also the distribution of the total final energy to end-uses is largely impacted by certain cyclic and non-cyclic environmental factors. To shed more light on how the demand is shared by buildings located in specific climate zones of the regions and how different energy performance policies can alter the need for energy in the future, the simulated annual changes of space heating, space cooling and hot water production energy demand are investigated. For simplicity, only the results for the Deep Efficiency scenario are presented, for climate zones where the floor area is projected to be the largest (equivalent with large population density).

As Figure 26 depicts, the largest energy demand in 2022 is found for the climate zones of 'Heating, cooling and dehumidification' and 'Cooling and dehumidification' in Centrally Planned Asia and South Asia, respectively. In Centrally Planned Asia, the 30% of heating (1.4 PWh), 74% of cooling (0.2 PWh) and 35% of HWP demand (0.3 PWh) of the 2022 level are outlined in this zone. The second and third largest demand in this region is estimated for climates with 'moderate and/or low cooling demand' (i.e., CIDs 3 and 6). Based on the Deep Efficiency scenario, the HEB model anticipates that the energy demand might be reduced for only the space heating until 2060, the other energy services could be characterized by growths in different extents.

In South Asia, the cooling need is determined to be the most significant form of demand in the most populous climate zone. It seems that if strict improvement in the energy efficient of South Asian building sector takes place, the need for space cooling can be curbed after an uphill stage might occur until 2035. Other regions for which the cooling is predicted to be the most dominant, but reducible end-use include Africa, Latin America and Pacific Asia. For the remaining regions, space heating is estimated to be the principal energy service. In these cases, the largest heating need emerges in the climate zones of 'Only heating with high and moderate heating demand' (i.e., CIDs 2: Former Soviet Union; 3: Eastern Europe), 'Heating and cooling' (CIDs 6: North America; 9: Middle East and Africa) and 'Heating, cooling and dehumidification' (CID 18: Pacific OECD). Based on the Deep Efficiency scenario, the corresponding demand is expected to be decreased by 2060 in the developed regions (e.g., North America), while the reduction might be less obvious in the developing regions (e.g., Pacific Asia).

As the previous examples have demonstrated the largest space heating need can typically occur under populous climate zones with HDDs over 1000°C/year (i.e., CIDs 3 and 6) (Table 2). For space cooling, the peaks could happen globally in zones with CDDs over 500°C/year (i.e., CIDs 13 and 16). In the climate zone of 'Cooling (moderate) and dehumidification', the simultaneous need for cooling and exhausting vapor from building interiors could elevate the demand remarkably. The global HWP demand, however, distributes more evenly throughout the climate zones, showing its maxima in CIDs 3 (Only heating with moderate demand), 2 (Only heating with high demand), 6 (Heating and cooling with low and moderate demand) and 16 (Cooling (moderate) and dehumidification).

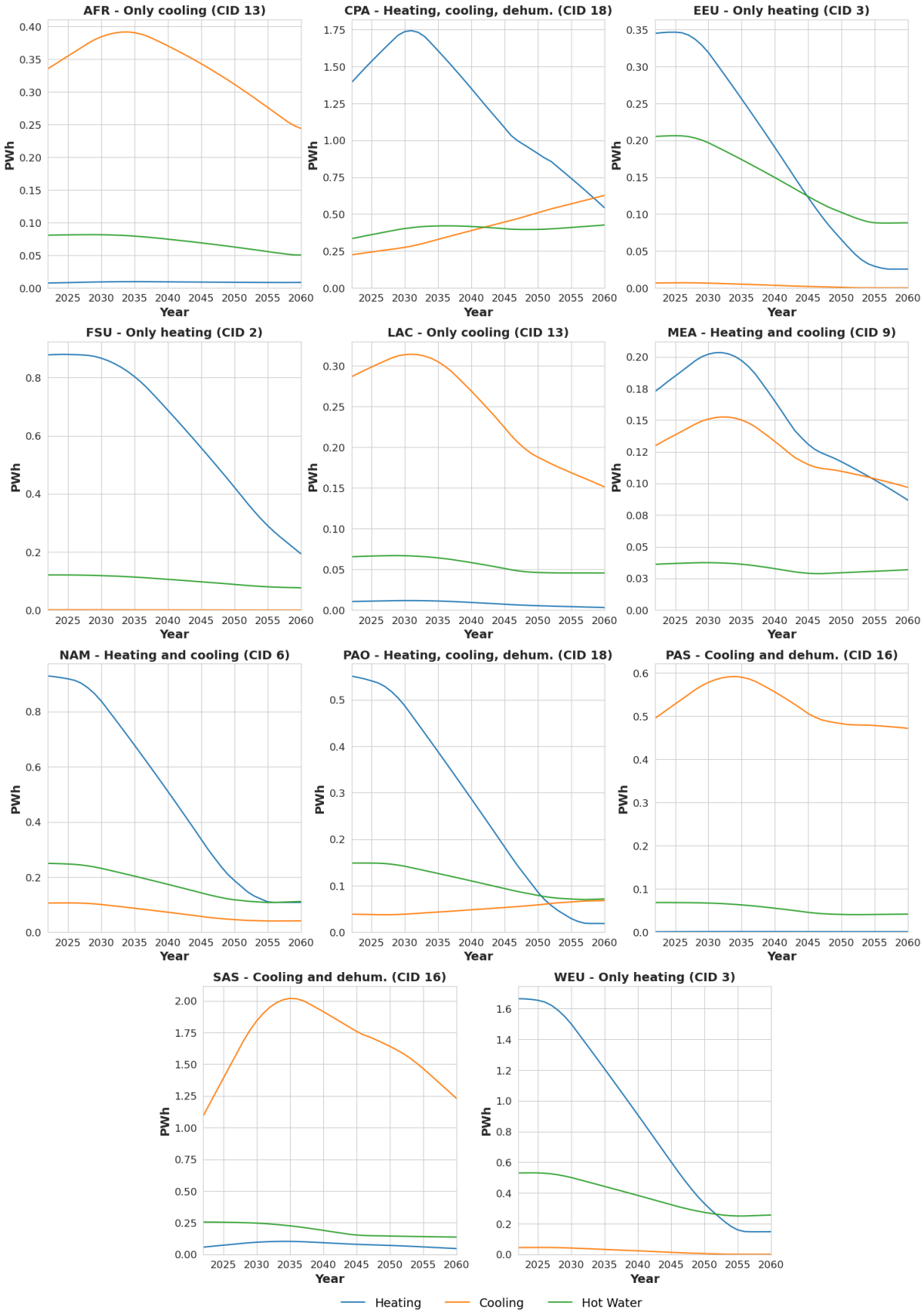


Figure 26. Regional energy demand for space heating, cooling and hot water production of the Deep Efficiency scenario for the period between 2022 and 2060 plotted for the most popolous climate zones

At smaller areal scale (e.g., countries), the climatic effect on the energy demand distribution can still be remarkable. Due to the size of the largest economies considered by the HEB, however, their climate zone-level annual demand profiles are very similar to that of their encompassing regions, Therefore, instead of presenting the corresponding year-to-year dynamics, it seems to be more reasonable to evaluate the intra-annual demand profiles estimated for these areas. For this purpose, like in the previous discussion, the simulated demand variations are shown on the basis of the values projected in the most populous climate zone of a given country. For brevity, now only the Deep case and the most pronounced demand type is highlighted for the years of 2022 and 2060.

In China, as it can be suspected based on the results of Centrally Planned Asia at Figure 26, the highest energy demand (space heating) is predicted for the 'Heating, cooling and dehumidification (CID 18)' climate zone, which shows its maxima during the end of December and early January (Figure 27). The HEB estimated that the vast majority of space heating occurs from November to the end of March. Apart from that period, need for space heating might be insignificant. However, it must be noted that in other climate zones (parts) of China, there could be minor heating-related energy consumption between March and November, but it is either sporadic or small as compared to the aggregated annual heating demand.

In the USA, the CID6 ('Heating and cooling with moderate heating and low cooling demand') is found to be the climate zone with the most floor space area among the potential HEB's climate zones. In these areas, the space heating curves have similar shapes to the Chinese case, although they are rather stretched towards the spring/autumn months. In other words, in climate zone in which the most US buildings might experience longer heating period (typically from middle of October to end of April) than in the Chinese climate zone.

The longest heating period is simulated for the EU (CID 3 – 'Only heating with moderate demand') where the majority of buildings are located in areas with all-year heating need. Since this climate zone of the EU is quite large, it can be concluded that the slight summertime heating need emerges in the northern parts of the zone (i.e., the UK, North Germany, North Poland and South Sweden; please refer to Figure 7) during the nocturnal hours. In the southernmost regions of this zone, on the other hand, the heating period could cover, similar to the USA case, the months between October and April (with peaks in January).

India is the only among the discussed sub-regions where the estimated cooling energy need exceeds the demand for heating. The corresponding period is projected to start at the end of March and ends at the end of November. In this climate zone (CID 16 – 'Cooling (moderate) and dehumidification') and in other parts of India, the cooling load is periodically completed with significant humidity due to the monsoon episodes, which yields its peak around August.

For this climatic region of India, the HEB model reveals a less optimistic future for demand by 2060, even by following the Deep Efficiency scenario, which would result in 4-fold demand peaks of cooling and dehumidification during the monsoon season. In the other highlighted economies, however, climatic effects might be reduced by promoting new building codes and improved energy performance of measures towards the middle of this century (Figure 27).

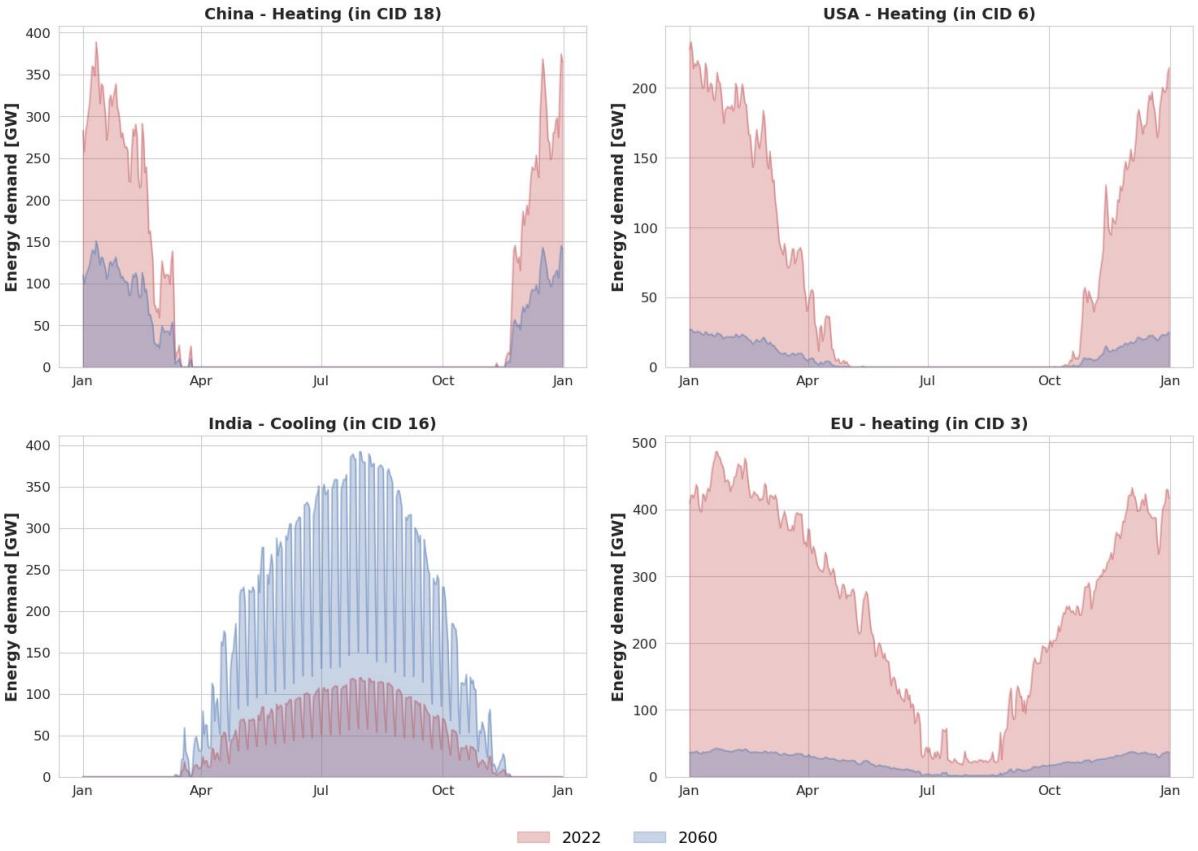


Figure 27. Intra-annual (2022 and 2060) energy demand profiles of the Deep Efficiency scenario plotted for the most popolous climate zones

4. Results and Discussion: Analyzing the onsite solar electric and thermal production potential

In order to step forward to a climate neutral building sector, it is desired to upscale the use of renewable energy sources to balance vast majority of the emerging energy demand. To explore the possibilities supported by solar PV/T technology, this section analyses the technical potential of rooftop integrated solar hybrid collectors on global and regional scale. In the next stage, the results of the BISE model are presented in terms of the future roof area availability projections, annual thermal and electric energy estimation for the entire building sector and separately for residential and tertiary buildings. Additionally, this section showcases the hourly profiles of regional energy production of PV/T collectors, which is crucial to understand the timing of peaks and troughs of the supply in the context of onsite energy balance. Lastly, a scenario analysis is performed in which a significant breakthrough of solar PV/T technology and its implication on the technical solar potential are discussed.

4.1 Global and regional distribution of projected annual suitable roof area

The global roof area available (suitable) to be covered with PV/T collectors is found to be 78.5 billion m^2 in 2022. By estimating an annual (relative) growth of around 5%, this value increases to 143.6 billion m^2 (Table 9). Regionally, noticeable differences are observed both in the annual values and in the growth rates. In 2022, the largest suitable roof area is projected for Centrally Planned Asia (24.2 billion m^2), North America (10.4 billion m^2), Latin America (8.7 billion m^2) and Pacific OECD (7.7 billion m^2). On the other edge, Eastern Europe (1.0 billion m^2), Africa (2.3 billion m^2) and Former Soviet Union (4.3 billion m^2) have the lowest estimated values. It is a clear tendency that the suitable roof area is anticipated to increase all regions during the modeling period, which is particularly pronounced in the developing regions (e.g., Pacific Asia: 7.8%/year, Middle East and Africa: 7.3%/year, Latin America 6.1%/year). In these regions, the expansion of the roof space is modelled to be slightly larger in the first half of the analysis time frame. In the light of the outlined trends, the most suitable roof area can be in Centrally Planned Asia (37.7 billion m^2), Latin America (20.8 billion m^2), Pacific Asia (17.2 billion m^2) and Middle East and Africa (13.0 billion m^2). In Eastern Europe and Former Soviet Union, however, minor changes are expected, with final values of 1.2 and 6.7 billion m^2. For more detailed analysis on the suitable roof area projections, please refer to Ürge-Vorsatz et al. (2023a).

Table 9. Regional values of projected roof area availability (in certain years; billion m^2) and its annual relative growth (between 2022 and 2060; %/year) used by the BISE model

Region	**2022**	**2035**	**2050**	**2060**	**Annual growth**
Africa	2.3	3.2	4.2	4.6	5.2
Centrally Planned Asia	24.2	27.0	31.4	37.7	4.0
Eastern Europe	1.0	1.0	1.1	1.2	3.1
Former Soviet Union	4.3	5.0	5.9	6.7	4.0
Latin America	8.7	12.6	17.5	20.8	6.1
Middle East and Africa	4.6	7.1	10.4	13.0	7.3

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North America	10.4	11.4	12.7	13.9	3.4
Pacific OECD	7.7	8.2	9.1	10.1	3.4
Pacific Asia	5.7	8.9	13.6	17.2	7.8
South Asia	4.5	6.4	8.1	8.7	5.0
Western Europe	5.2	6.3	8.2	9.7	4.8
World	**78.5**	**97.1**	**122.1**	**143.6**	**4.7**

4.2 Global and regional distribution of annual rooftop PV/T energy supply

The global technical potential of rooftop PV/T energy supply is modelled to be 54.8 PWh, with the shares of 69% and 31% for the thermal (37.8 PWh) and electric (17.0 PWh) energy forms (Figure 28). During the modeling period, the aggregated technical potential is projected to increase by 88%, with unchanged sharing among the thermal and electric part. Consequently, the BISE model estimated thermal and power production potentials of 71.6 PWh and 31.5 PWh by 2060.

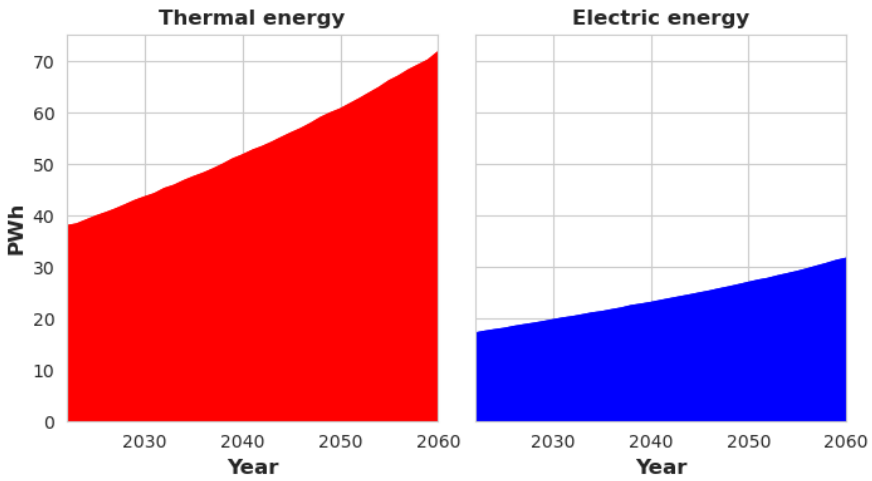


Figure 28. Global technical potential of rooftop PV/T thermal and electric energy production simulated by the BISE model for the 2022–2060 period

The simulated decomposition of global values to regional potentials depends on the changes in the roof area availability and the radiation incomes on the tilted arrays of rooftop PV/T collectors. Hence, due mainly to the size of the projected building stock, the most significant onsite solar energy supply is found for Centrally Planned Asia (17.7 PWh), Latin America (6.8 PWh), Pacific OECD (6.8 PWh) and North America (4.7 PWh) in 2022. The lowest estimated potentials, on the other hand, befall in Africa (2.0 PWh), Former Soviet Union (1.8 PWh) and Eastern Europe (0.6 PWh). By comparing Figure 29 and Table 9, one can conclude that the orders of suitable roof space and aggregated PV/T technical potentials show differences. In North America, for example, the free roof area is determined to be about 20% higher compared to Latin America, yet the solar energy production simulated for Latin America is about 45% more than that of North America. Therefore, it underlines that the radiation potential could also be decisive in exploring the possibilities of solar hybrid technology for the building sector. Nevertheless, the BISE model does not consider major fluctuations in the annual sums of solar

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irradiation, thus the future dynamics of the technical potential might rather be impacted by building characteristics.

As a result, the most pronounced technical potentials are revealed in Centrally Planned Asia (28.2 PWh), Latin America (16.3 PWh), Middle East and Africa (12.6 PWh) and Pacific Asia (10.7 PWh) by 2060. On the opposite side, Former Soviet Union and Eastern Europe can be found, with predicted potentials of 2.8 and 0.7 PWh. In Africa, for which also low energy production is modelled in 2022, there could be remarkable expansion due to the expected boom in the size of the building stock (2060: 4.0 PWh). This rapid expansion of the building stock results in the peak annual (relative) growths in the technical potential, particularly in the developing regions of Pacific Asia (5.4%/year), Middle East and Africa (4.7%/year), Latin America (3.6%/year) and Africa (2.6%/year). There are only three regions with simulated relative growths below 1%, namely North America (9‰/year), Pacific OECD (8‰/year) and Eastern Europe (5‰/year).

It is highlighted at Figure 29. that the fraction of the thermal and electric energy in the globally aggregated PV/T energy supply is generally fixed during the modeling time frame. Because of the climatic diversity of the analyzed regions, this is far from being the case on spatial level. There is a clear tendency that thermal energy, in line with the higher thermal efficiency, is produced more dominantly by rooftop PV/Ts. Based on the outlined differences, however, two region clusters can be identified. The first cluster contains regions where many of their sub-regions lie in the vicinity of the Equator. For these regions, the share of thermal energy production is around 70% (e.g., Middle East and Africa: 72%, Pacific Asia: 71%). For regions belong to the second group, this share is found typically to be under 60% (e.g., North America: 60%, Former Soviet Union: 56%). In the regions of the later cluster, the PV/T collectors drop their electric efficiency fewer and less frequently under daytime hours when their surfaces of the collector are strongly insolated and heated. In the meantime, less energy is absorbed and transferred by the coolant fluid flown into and out of the solar system. In order to shed light more on this phenomenon, this climatic effect will be discussed later in Section 4.3. through the intra-annual profiles of energy production.

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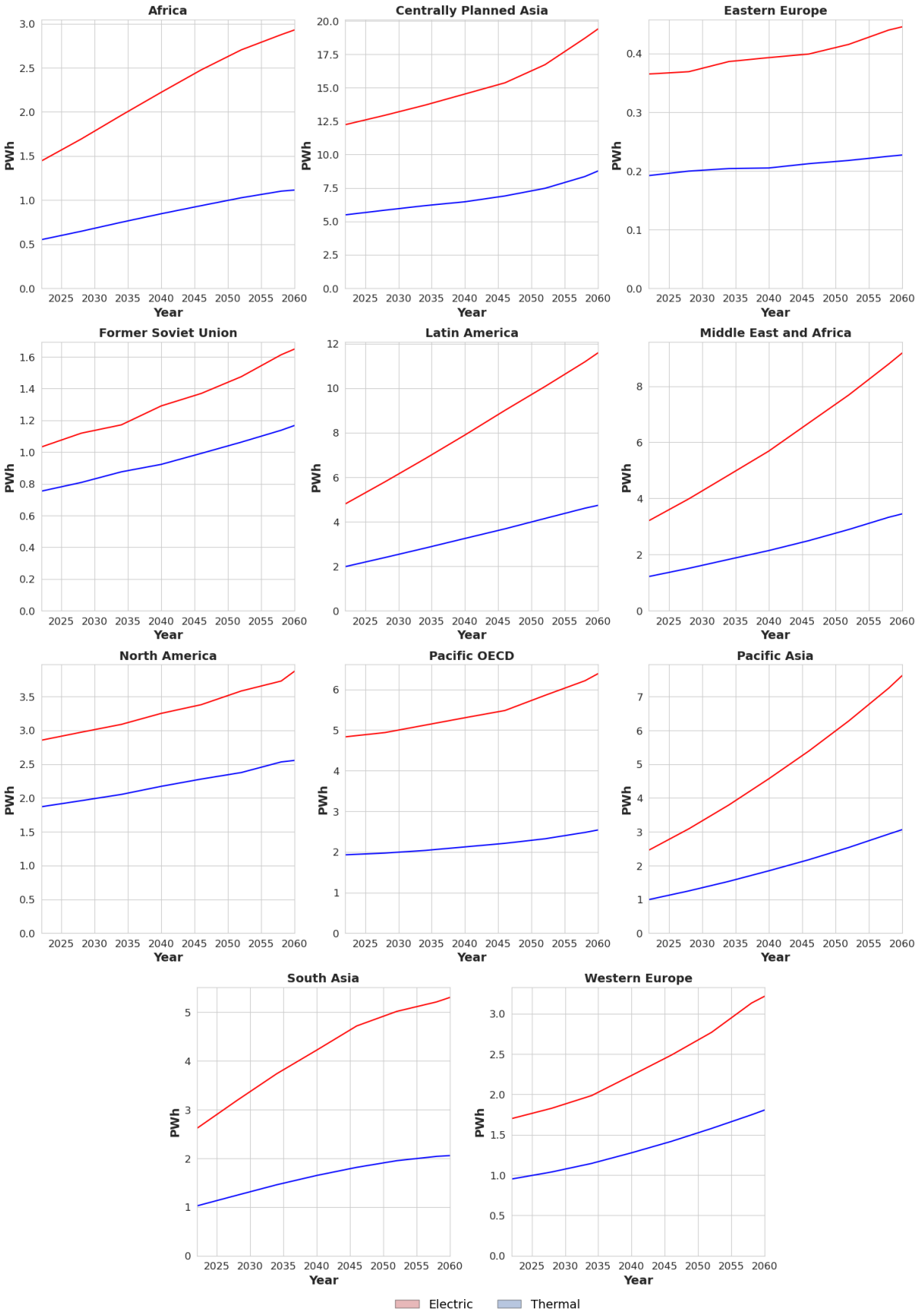


Figure 29. Regional technical potentials of rooftop PV/T thermal and electric energy production simulated by the BISE model for the 2022–2060 period

Utilizing rooftop solar energy requires different installation techniques and architectural solutions for various building types. Furthermore, the physical properties of buildings (e.g., height, façade to roof area ratio) could be crucial in determining the ability of a given building (type) in producing solar energy on its rooftop. Our modeling results exhibit that the residential building segment has theoretically the largest potential to utilize PV/T collectors on the horizontal surfaces, due to its estimated dominance within the stock. Precisely, if the building stock is shared between residential and tertiary buildings, the technical potential of rooftop PV/T energy production for the latter category is simulated to be 5 times larger globally in 2022. Highlighting first residential buildings, the related technical potentials have their maxima in Centrally Planned Asia (16.3 PWh), Pacific OECD (4.8 PWh) and Latin America (4.6 PWh) for the initial modeling year of the BISE (Figure 30). For the same year, the tertiary peaks are revealed for Latin America (2.2 PWh), Pacific OECD (2 PWh), Pacific Asia (1.2 PWh) and Centrally Planned Asia (1.2 PWh). If all regions are taken, the energy production potential of single and multifamily buildings is the most (least) significant in Eastern Europe (95%), Centrally Planned Asia (93%) and North America (89%) [in Pacific OECD (71%), Latin America (67%) and Pacific Asia (65%)].

The future dynamics of the regional, building type level solar energy production potential of rooftop hybrid collectors rely on the upcoming transformation of the building stock, indirectly via socio-economic factors (i.e., GDP and population). In spite of the non-negligible uncertainties, it seems to be likely that residential buildings may still preserve their dominance in the total PV/T technical potential over the tertiary type by 2060 (residential: 66.9 PWh, tertiary: 36.2 PWh). In general, the residential split is characterized with smaller increments during the analysis period, with regional peaks in South Asia (121%), Latin America (135%), Middle East and Africa (180%) and Pacific Asia (186%). On the other hand, slight increases (e.g., Western Europe: 3%) or even decreases (e.g., Centrally Planned Asia: –7%) are projected for many regions, stemming from the stagnation or shrink of the building stock and the available rooftop space (Figure 30). For the tertiary sector, apart from South Asia where lower number of buildings is anticipated for this category by 2060, the regional technical potential might be above the twofold than that of 2022 in many regions (Centrally Planned Asia: 951%, Western Europe: 370%, Eastern Europe: 300%, North America: 253%). In the less developed regions, however with lower magnitudes, there are still substantial enhances of the predicted technical potential visible, with changes around 100–150% (e.g., Former Soviet Union: 116%, Africa: 131%, Latin America: 153%). As a consequence of the rapid expansion of tertiary rooftops, the PV/T energy production for commercial/public building is modelled to have more potential in Western Europe and Pacific OECD by the middle of this century, compared to the residential rooftops. In the rest of the regions, the gap between the energy production of residential and tertiary PV/T collectors is found to be in a range from 8% (Centrally Planned Asia) to 91% (South Asia).

At this point, it is important to add that tertiary buildings can usually be classified as high-rise (e.g., offices) and midrise (e.g., retails) in terms of their mean height, so their related roof-to façade areas have low values. It means that applying wall and window integrated solar systems may lead to better area utilization and even higher solar potentials than that of rooftops integration. Yet, wider application of rooftop PV/T (combined with other) technology at both residential and tertiary buildings could be key in the energy transition of the building sector.

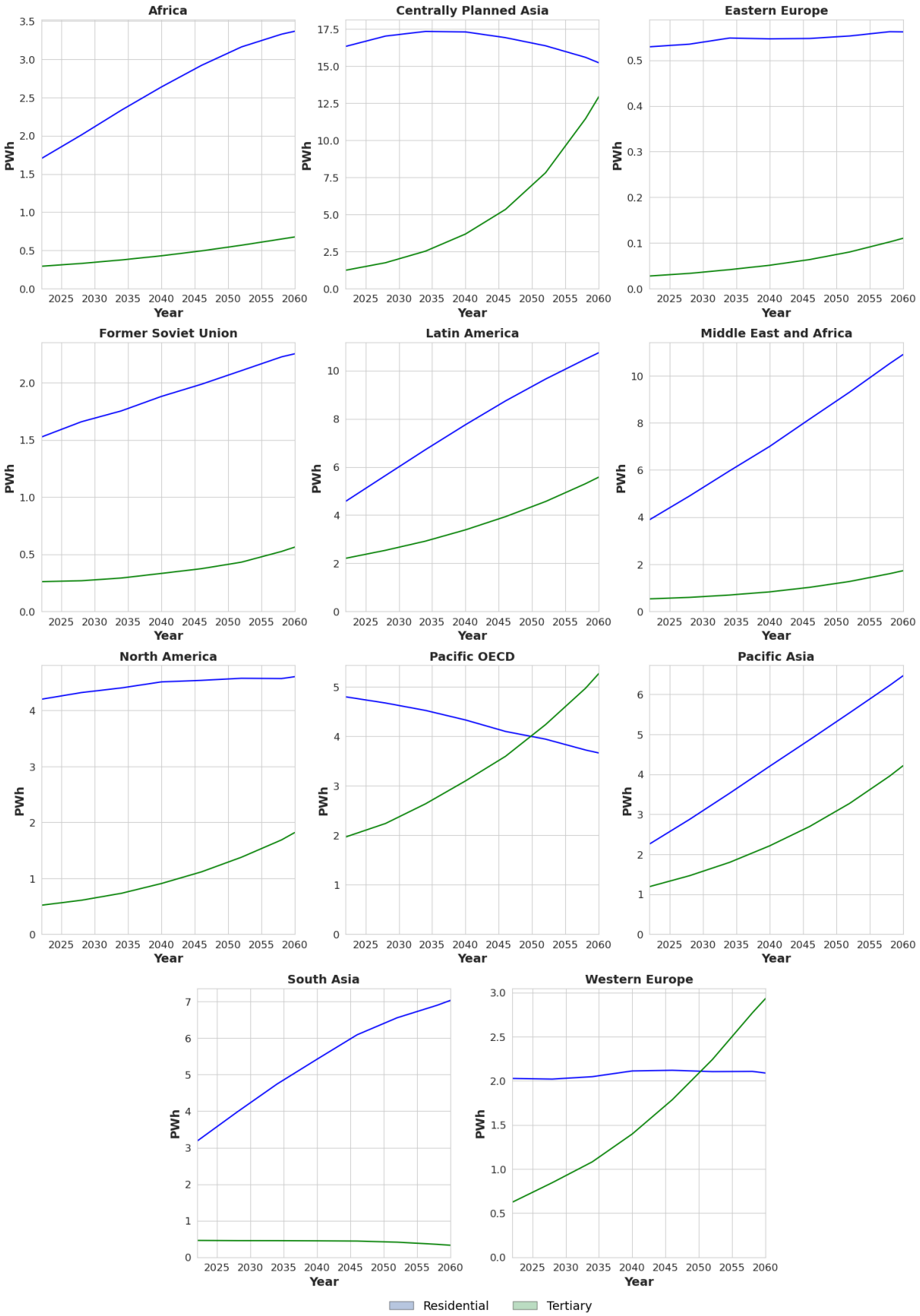


Figure 30. Regional technical potentials of PV/T energy production for the rooftops of residential and tertiary buildings simulated by the BISE model over the 2022–2060 period

4.3 Intra-annual distribution of rooftop PV/T energy supply in different regions

As it is concluded in the presentation of the year-to-year PV/T potentials (please refer to Figure 29), to better express the regional climatic effect on the solar energy supply, there is a need to zoom into the temporal dimension of the modelled results and scrutinize the intra-annual profiles of the aggregated thermal and electric energy production. Figure 31 summarizes these profiles for three years of the modeling period (i.e., 2022, 2050 and 2060). With the plotted curves, either the changes in the roof area availability or the seasonal characteristics of regional profiles can be identified. Since the earlier effect is discussed thoroughly in the previous section, now the results are presented from the perspective of the latter aspect. It is clearly outlined that the analyzed regions form three groups regarding the periods for maximum energy production. In regions with most of their areas in the Northern Hemisphere (i.e., Centrally Planned Asia, Eastern Europe, Former Soviet Union, Middle East and Africa, North America and Western Europe), the estimated peaks occur between the end of June and the middle of July. In South Asia, the monsoon period cuts off the summertime plateau, so the maxima are seen slightly earlier, typically in May. Since the Sun generally appears at its highest elevation between December and February in the Southern Hemisphere, rooftop PV/T collectors may generate the largest energy output over the Latin American buildings around mid-January. For Africa, Pacific Asia and South Asia, the predicted profiles can be typified with two peaks: one in March and one in October. The reason is related to the intra-annual migration of the intertropical convergent zone that causes frequent rain showers and overcast, seriously dampening the radiation income over certain areas of these regions.

If the variation of the profiles is considered as a factor expressing the level of fluctuation in PV/T production, it could determine the length of periods when solar energy is utilizable to equalize the demand side. All in all, the most balanced profiles are simulated for Pacific Asia, Africa and Latin America, based on the coefficient of variance statistics measure (2022: 4, 5 and 11%, respectively) (Figure 31). Contrarily, this coefficient is computed to be around and over 50% in 2022 for Eastern Europe (47%), Western Europe (50%), North America (53%) and Former Soviet Union (65%). The outlined profiles suggest that the regions with extended areas in the mid-latitudes and dominated by 4 seasons throughout the year could experience the most extreme temporal distribution of energy production. In these areas, thereby, the need for storing the energy surplus being generated during the peaks could be important to satisfy the energy demand of the periods with low production. In addition to this, the majority of the global population live in the mid-latitudes, hence solving energy storage could be a key to supply as much solar energy as feasible. Another conclusion on the basis of Figure 31 is that if the roof area continues rising at the pace projected by the BISE model, the gap between the production maxima and minima can grow further. Therefore, expanding the energy storage capacity could be a major challenge in the future.

The intra-annual rooftop PV/T profiles demonstrate that many regions can be characterized by pronounced and clearly distinguished maximum and minimum of energy production, generally during the periods with the lowest and highest Sun elevation. In the mid-latitudes, where high fraction of the worldwide buildings is located, those periods occur around the solar solstices when the daylight could be longest and shortest during a year. In solar energy production point of view, if the sky is clear, there is abundant available global radiation during the summer solstice (on 20th or 21st June in the Northern Hemisphere, on 21st and 22nd in the Southern Hemisphere). For this reason, the PV/T collectors receive high amount of energy, which is favorable for thermal energy production but less optimal for supplying electric energy (i.e., too high drop in the temperature-dependent electric efficiency).

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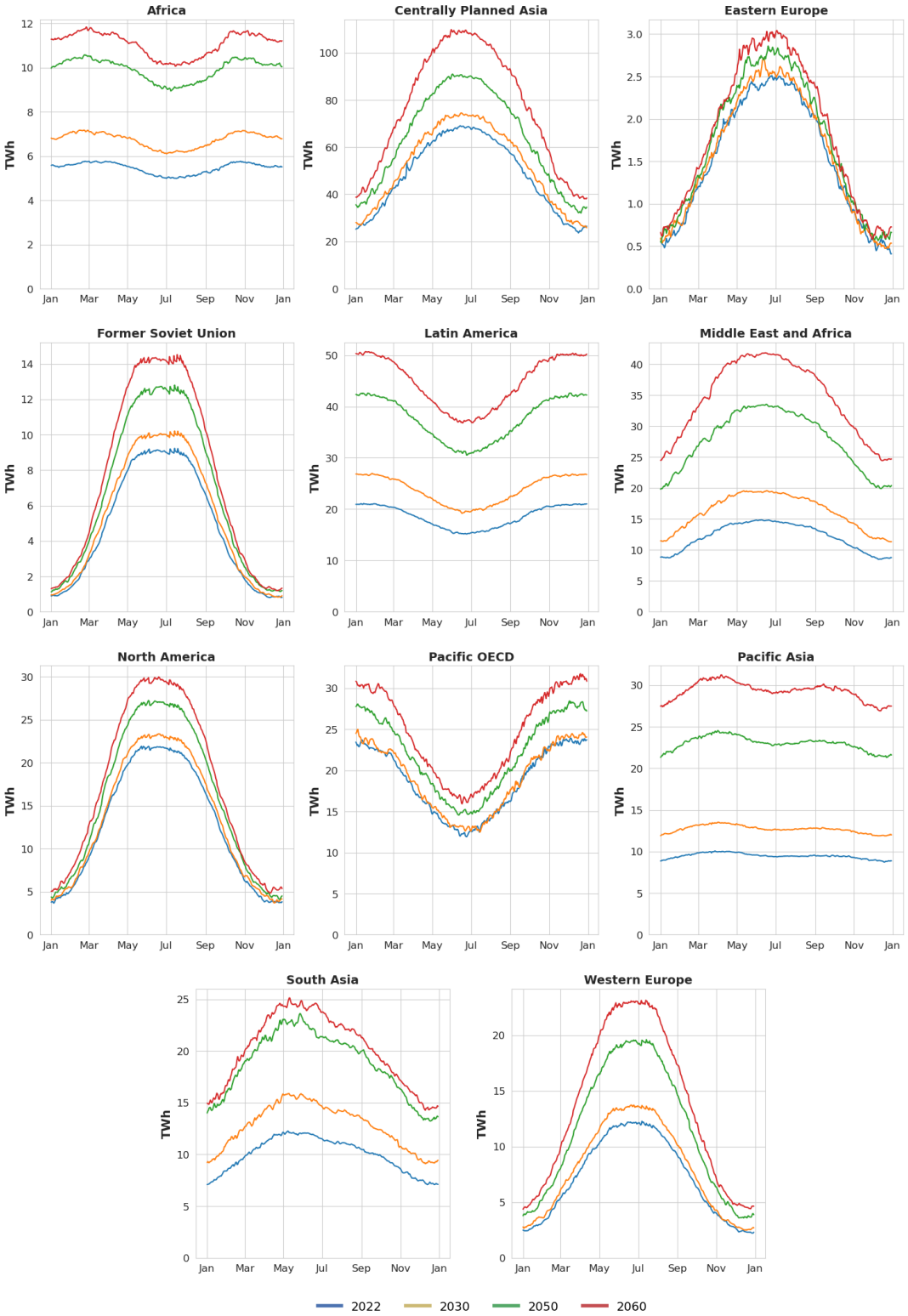


Figure 31. Hourly variations of regional technical potentials of rooftop PV/T energy production simulated by the BISE model over the years of 2022, 2030, 2050 and 2050

For producing electric energy with rooftop PV/T in the mid-latitudes, the end of the spring months might be more appropriate. In the vicinity of the Equator, the maxima (two peaks are simulated) happen in March and in the end of September, around the so-called solar equinoxes (on 21st March and 23rd September). The winter solstice, however, is generally followed by low solar energy production potential.

In order to present the intra-annual characteristics of PV/T energy production potential more in detail, different profiles are now shown for specific regions and days of the year. The regions are selected to represent all "profile clusters" illustrated in Figure 31 (i.e., single peak in June, single peak in January and two peaks). Besides, these curves are plotted for a single year (2022) and for the four astronomically highlighted days (i.e., solar solstices and equinoxes). To focus only the climatic influences and to eliminate the differences in the projected available roof spaces, the below profiles are illustrated in W/m^2 dimension.

In North America, which is a BISE region in the Northern Hemisphere with large areas in the mid-latitudes, the estimated profiles ("geographical potential") of the rooftop PV/T energy supply have its maximum and minimum during the summer (21st June) and winter solstice (21st December), respectively (Figure 32). The vernal and autumnal magnitudes, however, are in agreement both in the timing and magnitudes. The differences in the summertime and wintertime peak values are found to be about 4-fold and 3-fold in terms of thermal and electric production. It is also observable that the mean daily thermal energy generation is about 15 (winter)–85% (summer) larger than that of electric energy. The time of the daily peaks also shows slight lag between the thermal and electric outputs. For example, during the summer solstice, the electric energy production culminates about two hours later, which is time when the crystalline cells of the PV/T collectors start to cool (restoring electric efficiency) but the radiation is still strong enough to produce high amount of power. Thermal energy generation, on the other hand, could correlate better with solar radiation. However, it is not detailed now, but similar profiles are also simulated for Western Europe, Eastern Europe, Former Soviet Union and Centrally Planned Asia.

The Latin American case is quite the opposite relative to the North American case, so the maximum occurs during the winter solstice, while the minimum is outlined during the summer solstice (Figure 32). Naturally, it stems from the "hemispheric effect". Another major distinction between the two regions is the differences between the selected days, which is less significant based on the plot for Latin America and can be justified by the climatic heterogeneity of this regions. From the three selected regions, the highest absolute values of the thermal and electric outputs are simulated for Latin America. During the summer equinox, PV/T collectors could produce 160–180 W thermal and 50–70 W electric energy on 1 m^2 of their surfaces. These values yield that the production of thermal energy is very dominant, although with low variability between the four dates (summer: 136%, autumn: 148%). The time shift between the daily peaks of the electric and thermal energy generation, however, is very similar to the North American case.

The least pronounced seasonal variation is visible in Pacific Asia, with relative deviation ranges of 90 (winter) – 99% (summer) and 96 (winter) – 99% (autumn) compared to the vernal maxima of the thermal and electric energy supply categories (Figure 32). Consequently, as mentioned before, it implies a high degree of reliability and predictability in supplying solar energy by this type of technology. It is especially important (in energy transition context) in a region where the energy demand for cooling and dehumidification might be permanent over the year (please refer to Figure 20). The geographical features of this region also ensure that the length of the daylight does not change drastically within a year, hence the reliability could exist not only in seasonal but also in daily comparison. By following these trends, the thermal energy generation is modelled to be 133 (winter)

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– 149% (spring) higher than the auxiliary power production. Thus, these differences are in line with the values determined for North America, being one of the most potent BISE regions for producing thermal energy.

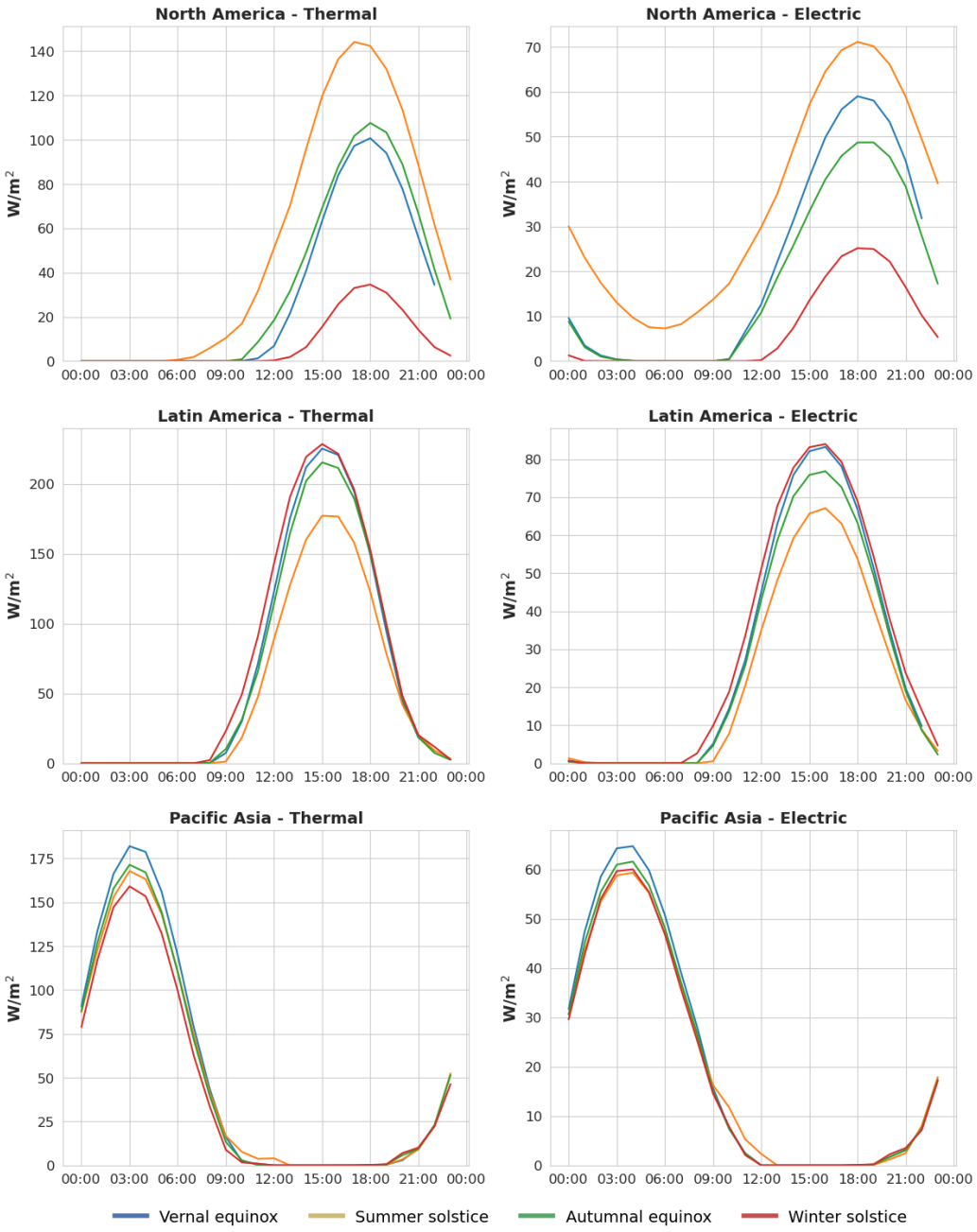


Figure 32. Hourly variations of modelled geographical potentials of rooftop PV/T thermal and energy production in North America, Latin America and Pacific Asia during the solar equinoxes and solstices of the year 2022. Please not that the seasons reflects to the "north hemispheric designation".

4.4 Scenario analysis

In the previous subsections, the annual and hourly profiles of the thermal and energy production of rooftop PV/T collectors are presented based on the “Baseline” scenario of the BISE model in which the technical potential is estimated for collectors installed on all unshaded and unobstructed rooftop spaces. Nowadays, however, the real installation coverage is much lower than this theoretical maximum. Besides, the reference simulation assumes that the performance of the hypothesized solar systems remain permanent during the modeling period, while the inactivity of the future technological progress of this technology is a rather an unlikely outcome over the next decades. On the contrarily, it can be anticipated that the appearance of new technologies and the reduction in payback period of PV/Ts could bring paradigm shift in the installation pace and lead to further enhance in the performance of these systems. By analyzing the results of the “Rapid technological progress” scenario of the BISE, a possible future case is intended to explore during which the spread and energy supply capacity of rooftop PV/T collectors are assumed to be very ambitious.

For 2022, the “Rapid technological progress” hypothesize that 10% of the available rooftops are covered by PV/T collectors, so that the corresponding regional solar energy production potentials are always 90% lower relative to that of the “Baseline” simulation (Figure 33). These values reflect to fact that the current energy production associated with rooftop hybrid solar technology is far below to its technical potential.

Taking a major (exponential) take-off in the installation demand of rooftop PV/Ts after 2022 into account, the gaps become reduced, having the levels between –49.2% (Eastern Europe) and –64.9% (e.g., Africa and Latin America) by 2030. Since the exponential trend is prescribed to be the same in each region, the above differences are dominantly resulted by the heterogeneous technical potential increases in the “Baseline” scenario. In Eastern Europe, where the technical potential is modeled to rise slowly, this reference value can be reached sooner though, particularly if high performance collectors get widespread after 2027. In the developing regions, the year-to-year speed of the newly installed solar systems in the “Baseline” and “Rapid technological progress” scenarios are estimated to be much closer, but without the infiltration of advanced PV/T collectors. For the same reason, the year when the technical potential of the “Baseline” case is reached by the other simulation is projected to be diverse. In Eastern Europe and Western Europe, this milestone occurs in 2034, while in most of the regions, it is predicted to happen four years later, in 2038.

By 2040, all regions experience the favorable effect of new, cutting-edge technologies on energy supply potential of PV/T collectors, hence the simulated values in the alternative scenario exceed well the reference technical potential, with relative values ranging from 28.6% (Former Soviet Union) to 58.8% (Pacific OECD). Generally, the most significant potentials are found for regions in which the 10-year intense technological development is considered to end by that time (e.g., Pacific OECD, Western Europe, North America, Eastern Europe and Centrally Planned Asia).

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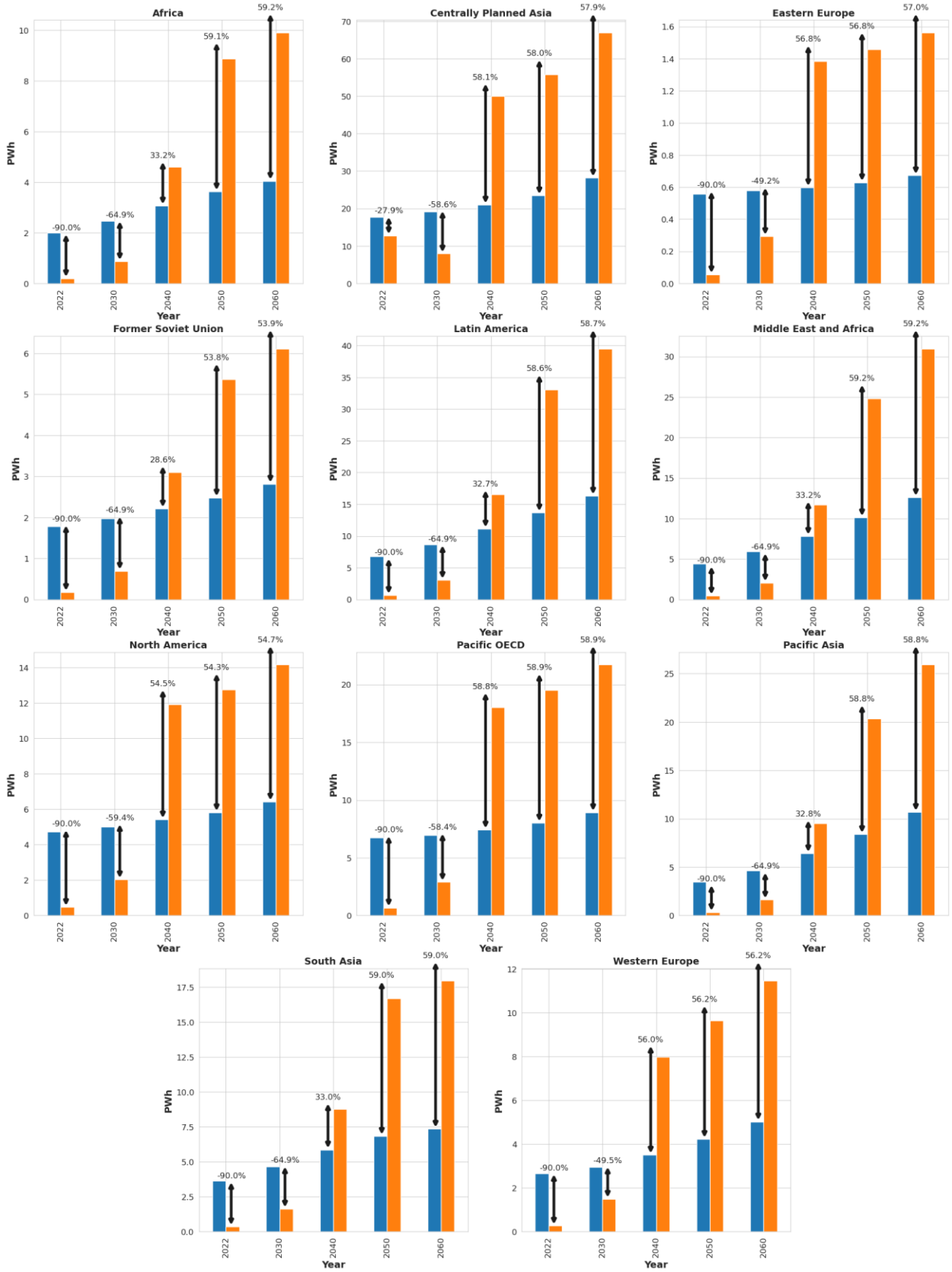


Figure 33. The regional comparison of the results for the "Baseline" and "Rapid technological development" scenarios of the BISE model simulated for the years 2022, 2030, 2040, 2050 and 2060

In the following years, the “Rapid technological progress” scenario assumes that the very efficient PV/T collectors continue to expand in the emerging economies, while this process is finished in the developed regions where this technology becomes standard in producing solar and thermal energy on building rooftops. As a result, the values in the alternative scenario are simulated to be above 50%, showing peak differences in Middle East and Africa (59.2%), Africa (59.1%) and South Asia (59.0%) by 2050. The bottom differences, in the meantime, are found in Western Europe (56.2%), North America (54.3%) and Former Soviet Union (53.8%). Since it is defined in the “Rapid technological progress” simulation that the thermal output can substantially be improved by high performance PV/Ts, the largest gaps between the two scenarios are detectable in regions with the best geographical potential for thermal energy production. After 2050, the advanced hybrid systems are assumed to produce 3 times more thermal energy in all regions as compared to that of in the “Baseline” case, therefore the differences in the regional potentials are not altered to the values revealed for 2050 (Figure 33).

The above scenario analysis has many theoretical implications that could help to shed light on the potential in applying high performance solar hybrid systems on building rooftops worldwide. It is clearly seen in Figure 33 that the technical potential of the rooftop PV/T energy production is immense. Still, due primarily to the installation and maintenance cost of hybrid systems, currently this technology has a small share in the total solar market (Lämmle et al., 2020). Yet, the actual energy prices support the upscale of solar technologies, though there is major competition between different technologies. One of the main advantages of hybrid technology over other solutions is that it provides electric and thermal energy simultaneously, which can satisfy most of the energy demand for space heating/cooling and hot water production at the same time. That is the reason why PV/T technology has already been proven to be effective in obtaining net-zero energy buildings (e.g., Yang and Athienitis, 2016) and is anticipated to have increased contribution to the renewable energy production during the following decades.

For the whole building sector, however, reaching the net-zero energy status relying only on PV/T technology seems to be unrealistic, owing to, for instance, climatic and financial constraints in different regions. Still, especially in hot climates, PV/T collectors could be great tools to balance the onsite energy demand over most of the year. As the scenario analysis shows that to explore the entire potentiality of this technology, it is crucial to increase the installation pace well above the speed of the construction of new buildings. Additionally, there is a need to test and explore the effect of the latest PV/T productions, since cutting-edge systems can provide much more energy yields than conventional ones, which is especially important over areas where the available radiation energy has high variability in space and time. For the same reason, applying electric and thermal energy storage (TES) solutions would be important to operate as “backup systems”. Nevertheless, the cost of storage technologies is still quite high, which is a remarkable barrier needed to be tackled in the near future. Consequently, despite the intense technological penetration of batteries and TES equipment (e.g., water tanks, sorption, phase-changing materials) as well as drop in the related prices, financial support programs must be built on different administration levels to be able to utilize as much of the technical potential as feasible.

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5. Analyzing energy and carbon lock-ins, CO_2 emission and net-zero potential of the building sector

5.1 Global energy lock-in

As it is demonstrated by the HEB simulations earlier in Section 3.1., the possibilities to decarbonize the building sector over the next decades could have wide spectra either globally or regionally, depending on the actual and future policies are followed. In this section, a brief analysis is presented to highlight that despite the high levels of building-related energy consumption and CO_2 emission recorded nowadays, combining very ambitious energy efficiency measures and onsite renewable energy sources, major improvement can be made by the middle of this century.

The need of modernizing the building and construction sector in a way that reduces lock-in risks is emphasized by the Paris Agreement, as energy and carbon lock-in will gravely imperil or significantly postpone attaining net-zero commitments by decades (Urge-Vorsatz et al., 2020). Here lock-in refers to an act which constrain the rate and magnitude of energy and carbon emissions reductions in the coming decades (Seto et al., 2016). The results of HEB model (refer to Figure 34) show that if the energy performance of new and retrofitted buildings do not improve at all or just slightly, while advanced buildings spread only in the limited areas of the World (please refer to the definition of the Frozen Efficiency scenario; Table 1), the energy demand could grow by 80% by 2060 compared its current level. On the other hand, if the energy performance of new buildings are higher, deep renovation results in 30% energy demand reduction and advanced buildings with very low energy efficiency measures become standard in most regions (Deep Efficiency scenario), about 53% of the estimated demand for 2022 could be reduced by the end of the modeling period. It means that there is a lock-in effect of more than 130% between these two highlighted cases, which underlines the urgency of introducing more stringent policies as soon as possible. However, the less ambitious Moderate Efficiency scenario also indicates expansion in the energy demand towards 2060, the related lock-in gap is smaller, which implies that, due to the size of the building stock, even smaller development in the energy performance codes and renovation rates could have its visible impact on the energy demand.

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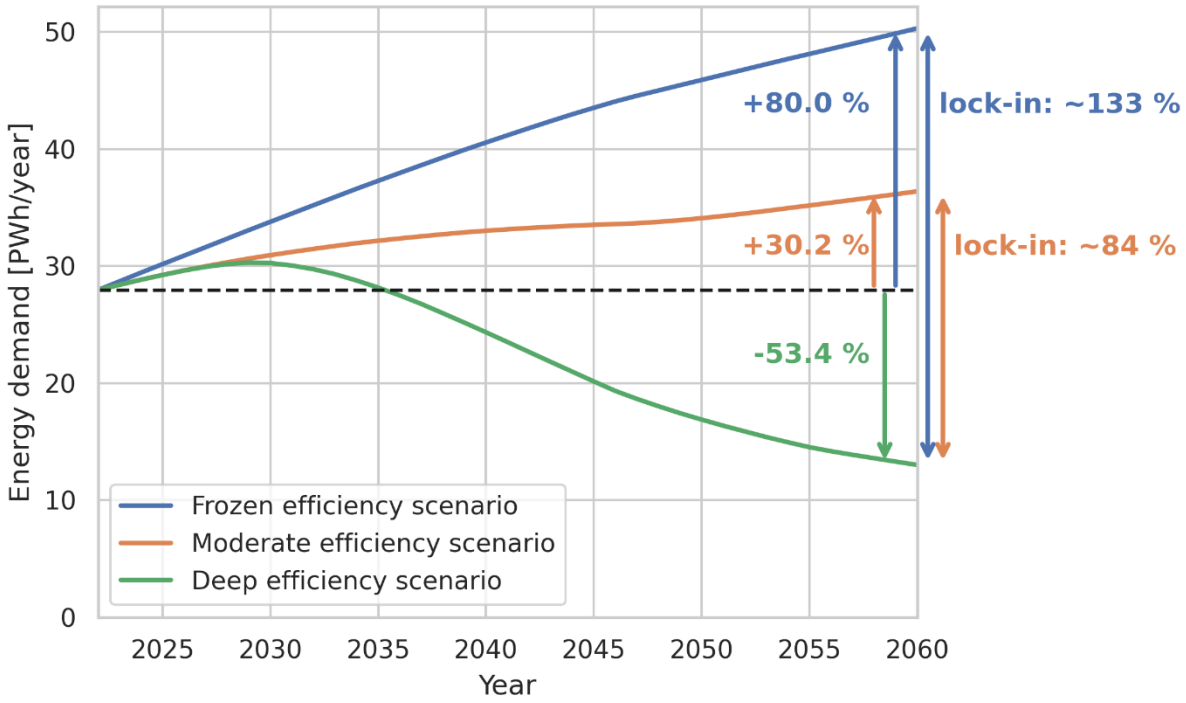


Figure 34. Modelled changes of the global energy demand in the different HEB scenarios over the period 2022–2060. Based on the results for 2060, the related lock-in effect is also illustrated.

5.2 Estimation of regional CO_2 emission and global carbon lock-in

Since the building sector has about 40% contribution to the total greenhouse gas emission, the reduction of the energy demand is a must to be able to tackle the adverse outcomes of the climate change and to bring closer the climate neutrality goals declared in the Paris Agreement. The HEB model estimates the building-related aggregated CO_2 emission of space heating, space cooling and hot water production to be 9.3 Gt globally in 2022 (Figure 35). Since the largest modelled energy demand is related to space heating, the most significant split in the total emission is caused by this end-use type. As a result of the projected tends in the energy demand by different scenarios, the global CO_2 emission is anticipated to substantially elevate if the less favorable policy assumptions are followed (Frozen Efficiency: 0.22 Gt/year, Moderate Efficiency: 0.09 Gt/year), while after a short growing period, it reduces by a rate of 0.12 Gt/year. Therefore, by 2060 the CO_2 emission are simulated to be 18.1, 12.9 and 4.7 Gt in the Frozen, Moderate and Deep Efficiency scenarios, respectively.

Regionally, in line with the regional demand estimations as well as with the inputs for regional fuel splits and emission factors, the CO_2 emission presents its largest values in Centrally Planned Asia, South Asia, Western Europe and North America (Figure 35). In the Frozen Efficiency scenario, the emission has the largest modelled increases in South Asia (233%), Middle East and Africa (171%) and Centrally Planned Asia (146%). On the other hand, the lowest changes are modelled for Pacific OECD (–2%), Eastern Europe (11%) and North America (12%).

Based on the policies in the Moderate Efficiency scenario, there could be two groups of regions in terms of the nature of the simulated changes in the emission. In the developing regions, the CO_2 emission is estimated to elevate during the modeling period, particularly in South Asia (160%), Middle East and Africa (112%) and Pacific Asia (83%). In such regions as Western Europe, Eastern Europe,

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Pacific OECD, North America and Former Soviet Union, contrarily, there are emission reductions in a range between –70% (Western Europe) and –4% (Former Soviet Union).

In the Deep Efficiency scenario, apart from South Asia, the projected values decrease significantly between 2022 and 2060. Therefore, considering better energy performance of buildings and improved emission factors, there might be a reduction potential of 40–80% to curb CO_2 emission by 2060 in most regions.

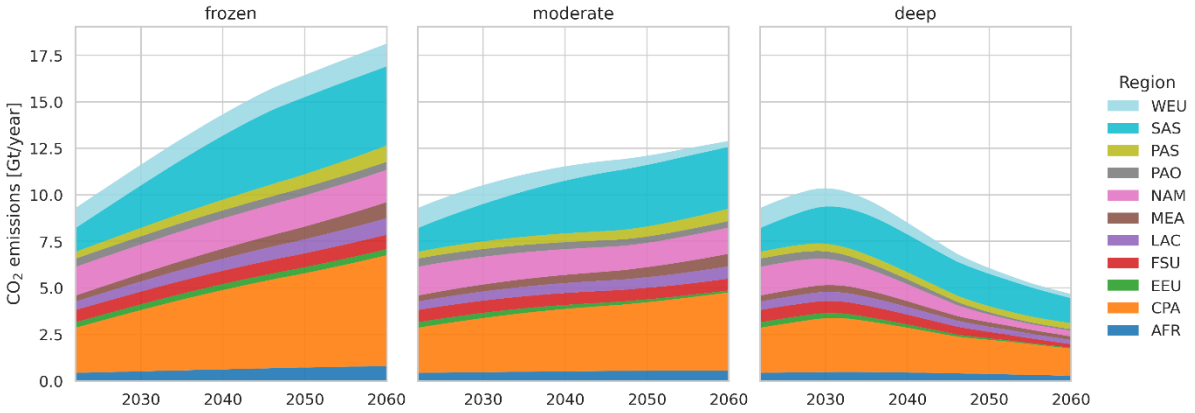


Figure 35. Modelled regional changes of the CO_2 emission in the different HEB scenarios over the period 2022–2060

Figure 35 andFigure 36. confirm that without improving the renovation rate and energy efficiency of existing and newly built buildings, not only the energy demand but also the carbon emission is anticipated to skyrocket in the next decades. Precisely, it is seen that the resulting lock-in effect could be as high as 145% if the future emission trend will be similar to that of the Frozen Efficiency scenario. Since the HEB model estimates the CO_2 emission stems directly from the energy usage and does not take the embodied emission into account, the lock-in effects could be much higher than the ones concluded between the Frozen/Moderate Efficiency and the Deep Efficiency cases. The main explanation for this could be related to the advanced buildings that are usually constructed by employing sustainable and less carbon intensive materials. Given that the difference in the shares of the advanced buildings within the stock is assumed to be the largest by the end of the modeling time frame, the effect of the embodied CO_2 emission on the total emission may be increasingly highlighted over the time.

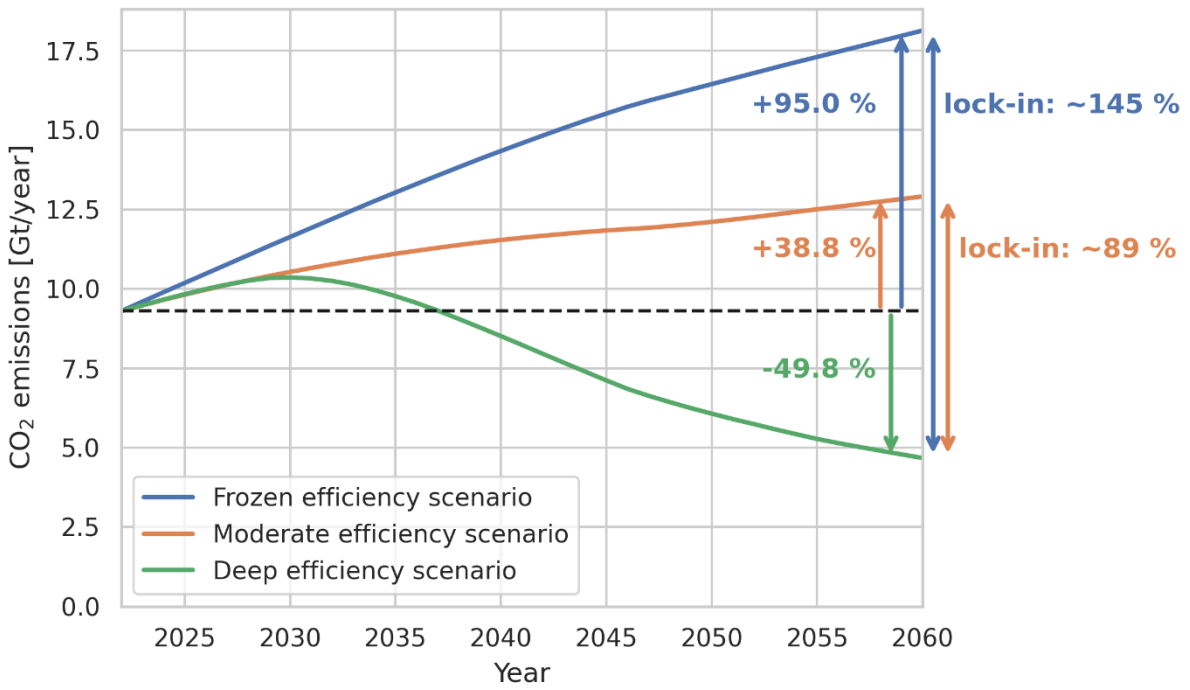


Figure 36. Modelled changes of the global CO_2 emission in the different HEB scenarios over the period 2022–2060. Based on the results for 2060, the related lock-in effect is also illustrated.

5.3 Net-zero potential of buildings in different regions

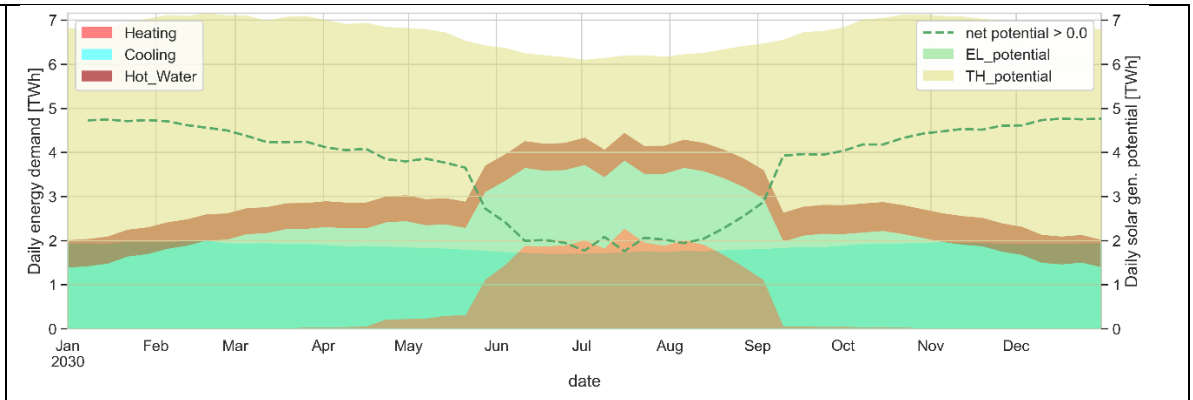
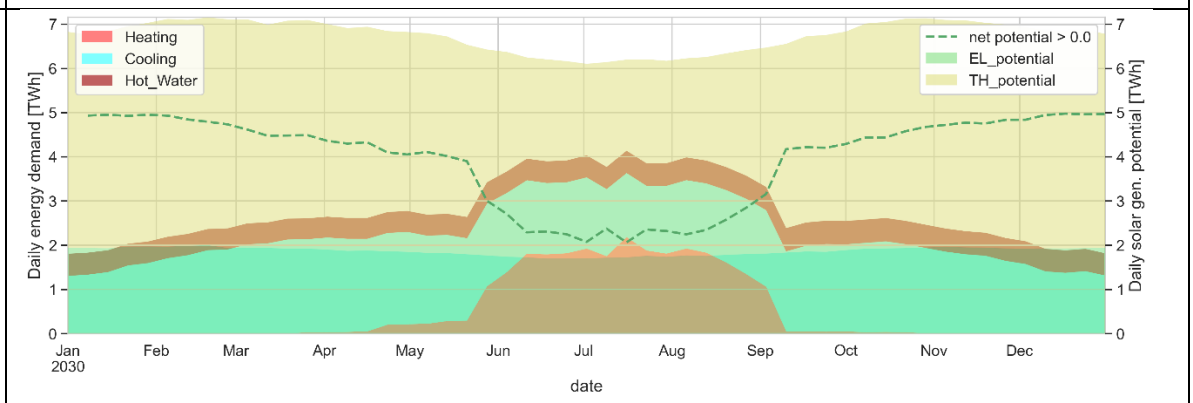
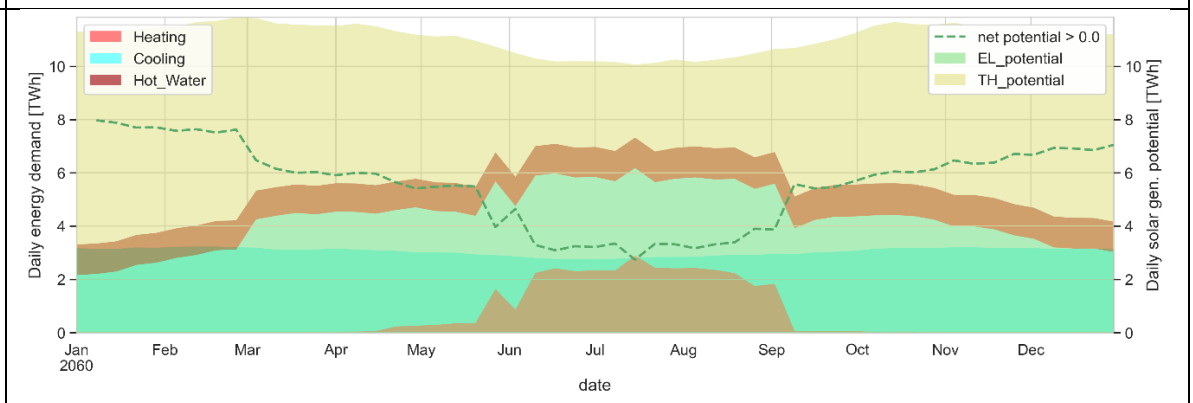
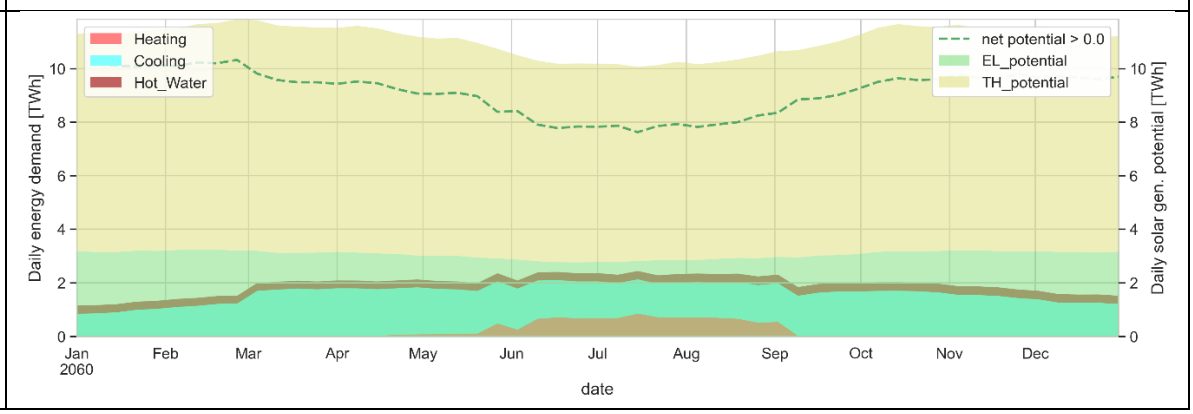
The results for the annual energy demand carried out with the Net Zero Energy scenario provides modeling evidence on that global and regional energy demands can be curbed to a nearly zero level if the building sector applies ambitious energy performance policies as well as utilizes onsite renewable energy supplied by solar technology. The simulations of the BISE model show that there is immense energy production potential of rooftop PV/Ts, which could be, at least in its magnitude and annually, could be suitable to balance the local energy demand of the building sector. In order to explore the possibilities that hybrid solar system can offer more in detail, the simulated energy demand of the HEB model and the energy production given by the BISE model are contrasted on hourly basis. The outcomes below could help to understand the spatiality and temporality of how the energy production rooftop PV/T collectors can cover the demand and inform on the periods when mismatch emerges between the demand and supply sides.

5.3.1 Africa

In the region Africa, due to the significant and temporally balanced geographical potential for radiation, the technical potential of rooftop PV/T production is predicted to be sufficient to satisfy the energy demand for space heating, space cooling and hot water production throughout the entire day, irrespective to the analyzed scenario and year (Table 10). The least surplus of the production occurs during the summer when the cooling need is modelled to be substantial, but it seems that even in the least optimistic Frozen Efficiency scenario, there is no mismatch visible neither in 2030, nor in 2060.

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Table 10. Comparison of the HEB's hourly building energy demand and the BISE's technical potential of rooftop PV/T energy supply for Africa

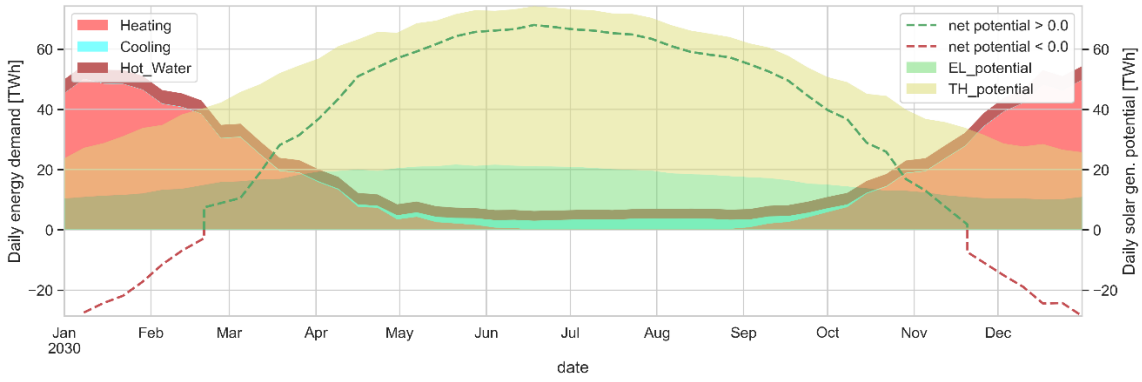
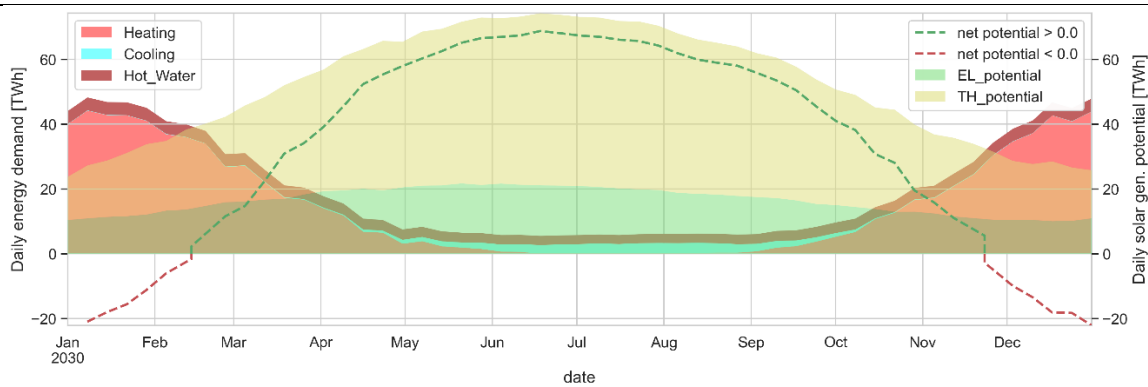
Frozen (2030)	
Deep (2030)	
Frozen (2060)	
Deep (2060)	

5.3.2 Centrally Planned Asia

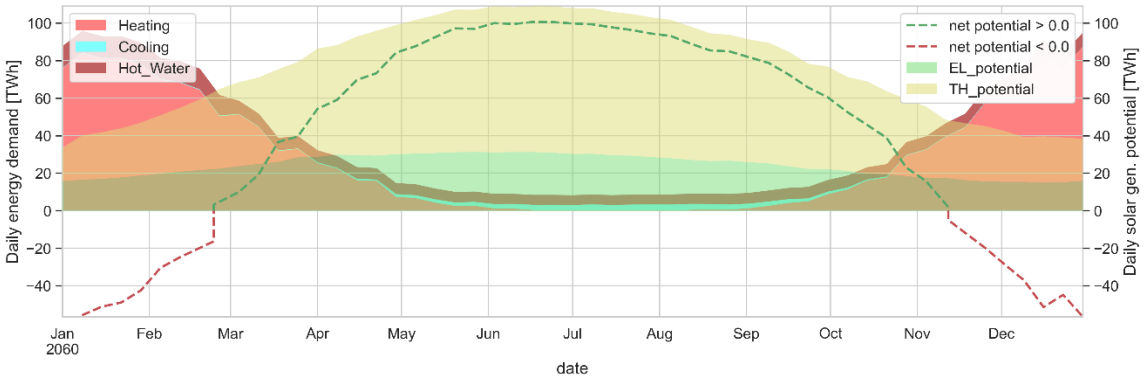
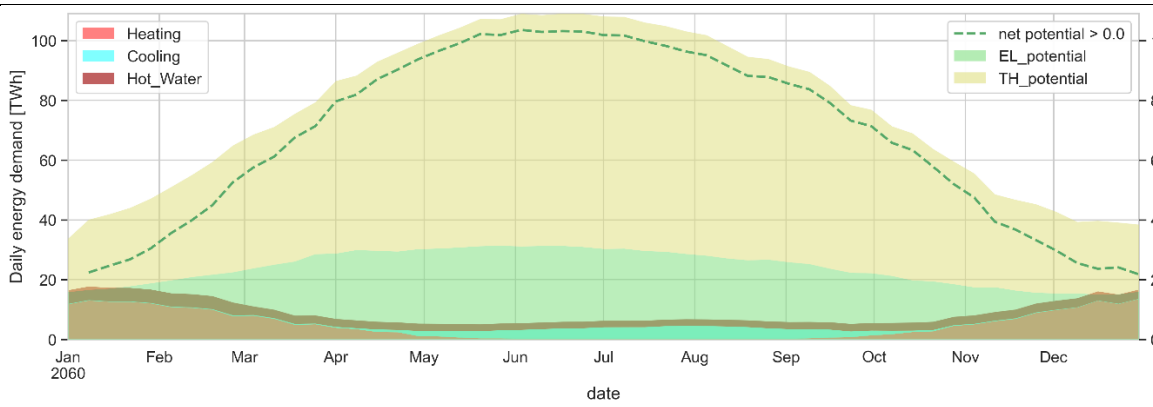
Centrally Planned Asia can be characterized by two very different stages during the modeling years (Table 11). In 2030, there is an agreement between the two scenario cases in that the wintertime demand dominated by space heating and hot water production is much larger than the available PV/T thermal and electric potential, thus solar energy sources do not seem to be sufficient to solely compensate the demand, there is a need to use other alternatives to reach the balance. During the summer months, however, the energy demand for space cooling is not estimated to be as high as the supply side, so there is abundant thermal and electric energy to cover the emerging needs. By 2060, the above situation remains the same in the Frozen Efficiency scenario. The demand and supply are modelled to increase simultaneously, which makes the length and magnitude of the surplus and mismatch periods unchanged.

The data for Centrally Planned Asia clearly shows that based on the onsite solar energy production, during winter session the demand for thermal energy is substantially higher, primarily dominated by the demand for hot water energy, than the onsite solar electric and solar thermal production. However, apart from the four months in the winter session, in rest of the months in a year, only the solar electric production is sufficient to meet the thermal energy demand. Thus, in Centrally Planned Asian region, storage would play pivotal role to decarbonize the building sector.

Table 11. Comparison of the HEB's hourly building energy demand and the BISE's technical potential of rooftop PV/T energy supply for Centrally Planned Asia

Frozen (2030)	
Deep (2030)	

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Frozen (2060)	
Deep (2060)	

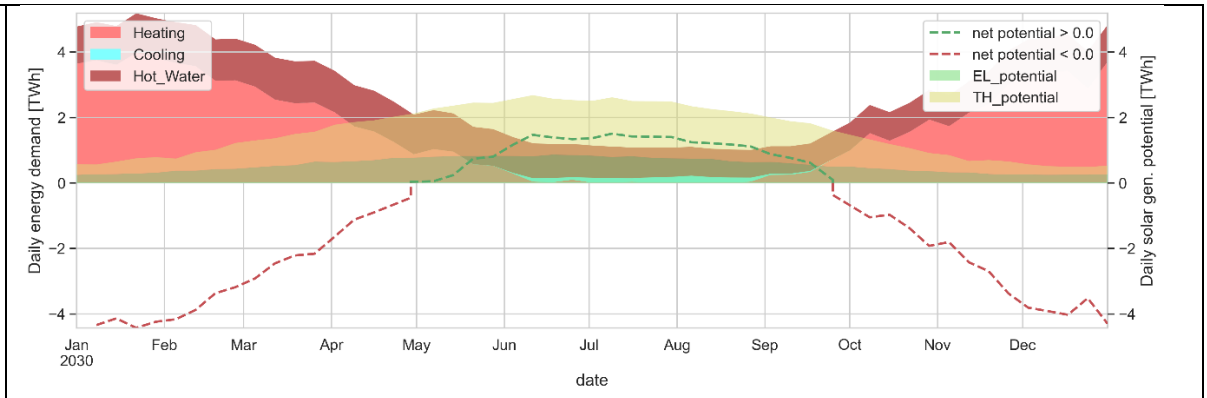
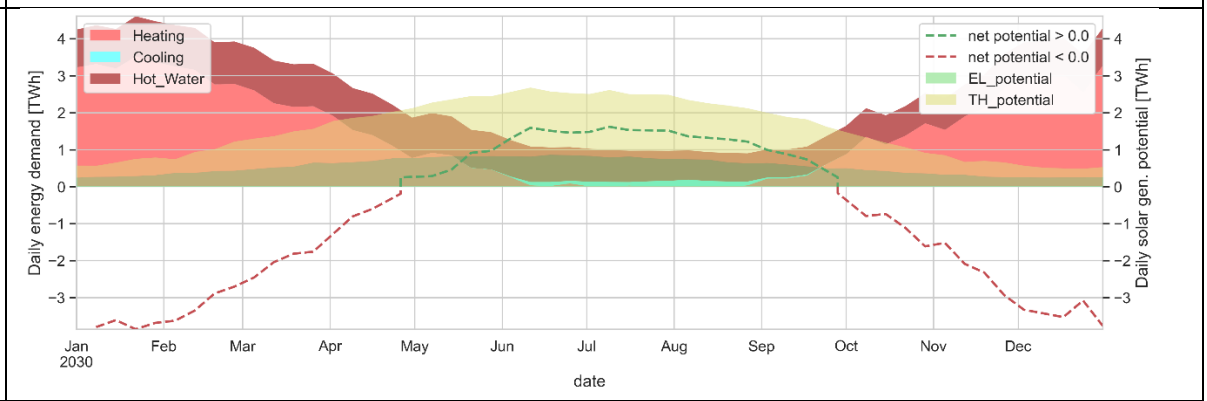
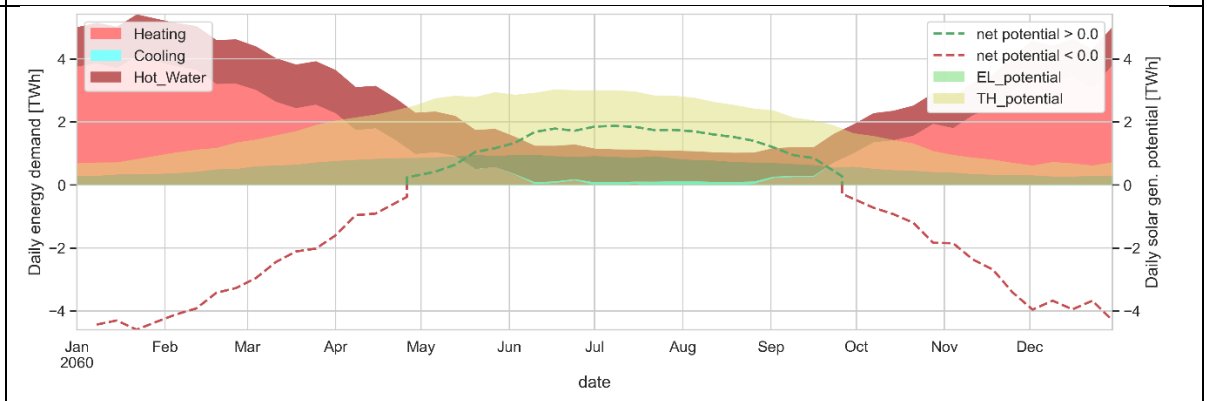
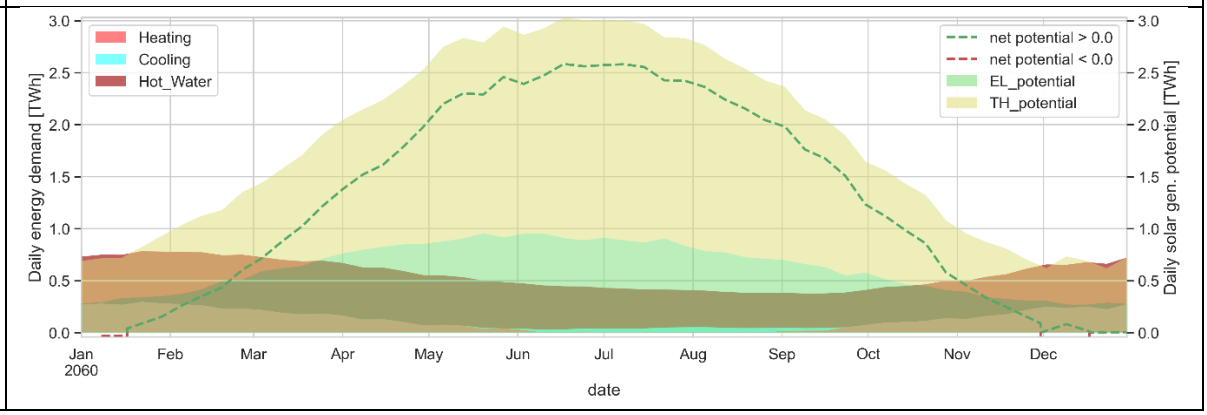
5.3.3 Eastern Europe

In Eastern European region, the Deep Efficiency scenario shows the significance of implementing demand measures as in this scenario, most of the days, precisely 331 days in a year (refer to 2060 data) onsite solar energy can meet the thermal energy demand as the demand is substantially lower compared to the Frozen Efficiency and Moderate Efficiency scenarios (Table 12). However, for the Frozen and Moderate Efficiency scenarios, energy demand on most of the days in a year cannot be met by onsite solar energy production.

The energy demand by 2030 as per our modelling assumptions (refer to Chatterjee et al. (2022a) will not be reduced much as market needs time before the energy renovation rate and new construction rates accelerate. Thus, the net-zero potential in 2030 is minimum in all the scenarios in Eastern European.

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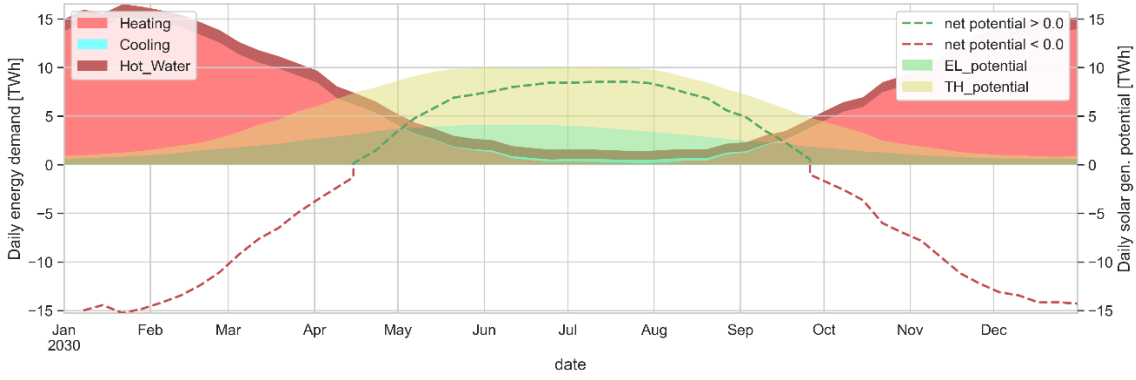
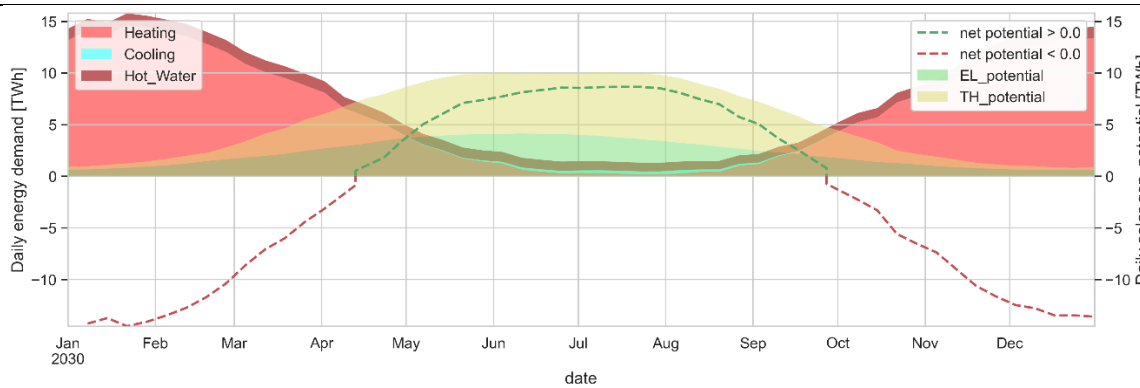
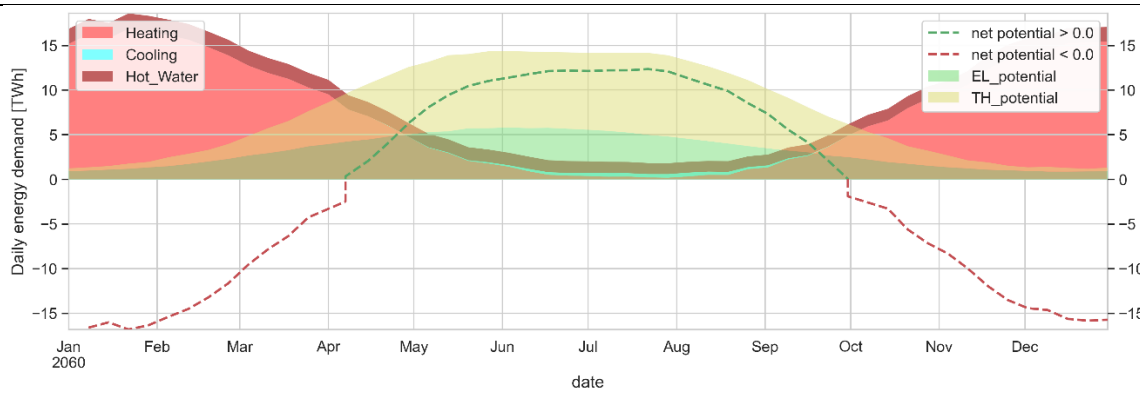
Table 12. Comparison of the HEB's hourly building energy demand and the BISE's technical potential of rooftop PV/T energy supply for Eastern Europe

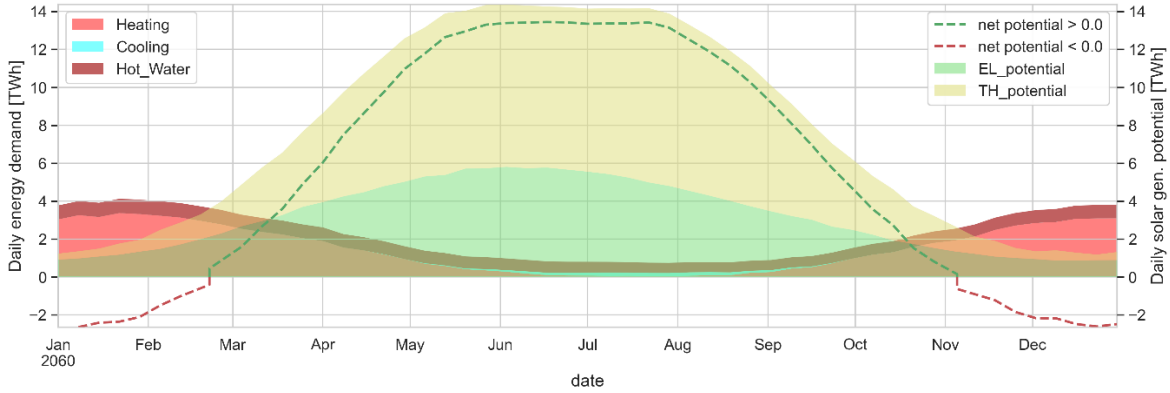
Frozen (2030)	
Deep (2030)	
Frozen (2060)	
Deep (2060)	

5.3.4 Former Soviet Union

For Former Soviet Union, the thermal energy demand often does not get met by the roof energy production, especially in the winter season (Table 13). Even in the Deep Efficiency scenario, the net demand is around 2 TWh in 2060 during the winter period under the Deep Efficiency scenario. However, because of the high-efficiency measures implemented under Deep Efficiency scenario, the net demand stays well-below 5TWh, but under Frozen Efficiency scenario, it goes well-above 10 TWh in some months in the winter. Thus, the data for Former Soviet Union proves one of more time the significance of implementing the demand measures.

Table 13. Comparison of the HEB's hourly building energy demand and the BISE's technical potential of rooftop PV/T energy supply for Former Soviet Union

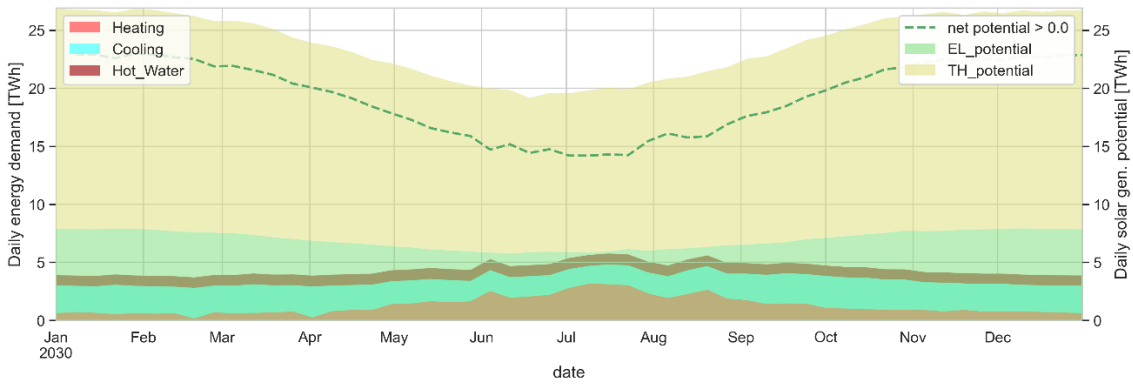
Frozen (2030)	
Deep (2030)	
Frozen (2060)	

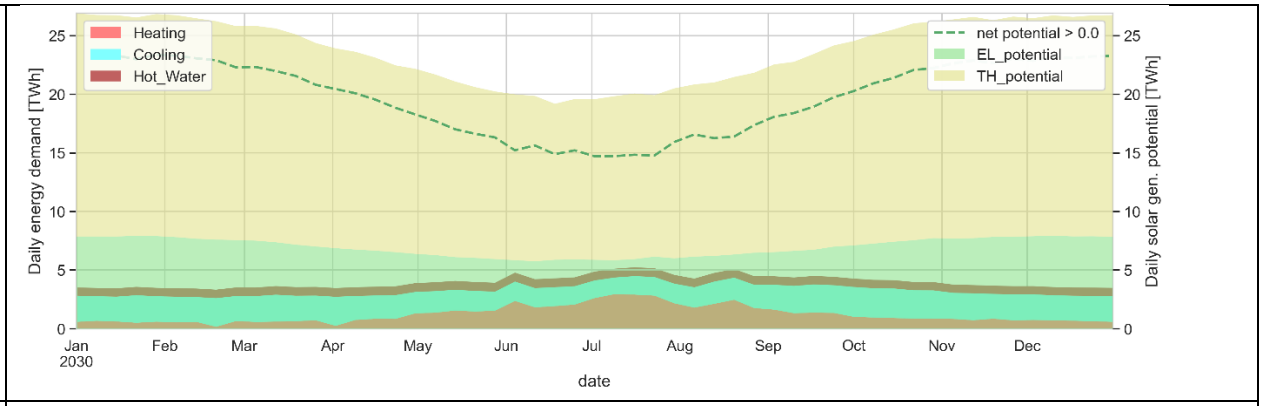
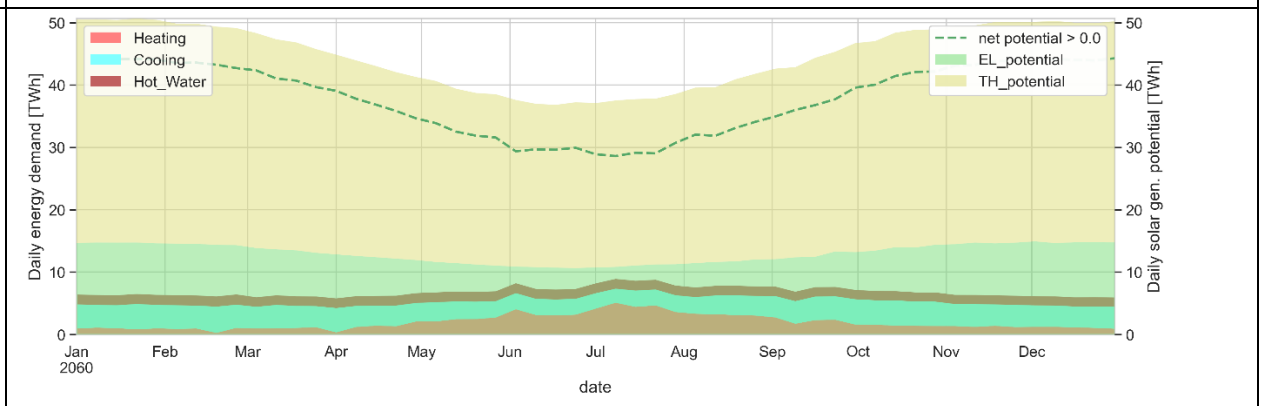
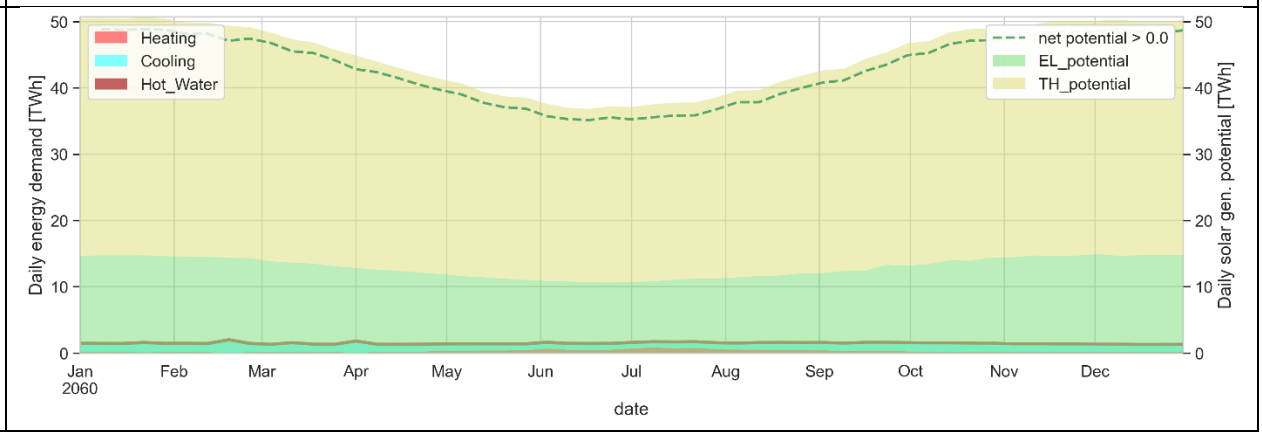
Deep (2060)	

5.3.5 Latin America

For Latin American region, due to the immense potential in onsite solar energy production, energy demand can be met with onsite energy production throughout the year irrespective of scenarios. However, in this analysis, we are considering both solar thermal and solar electric production with the total demand, but, solar thermal usually get used in meeting hot water demand only. Nonetheless, even if we consider only the solar electric production, building sector in the Latin American region can achieve net-zero by 2060 (refer to Table 14 below).

Table 14. Comparison of the HEB's hourly building energy demand and the BISE's technical potential of rooftop PV/T energy supply for Latin America

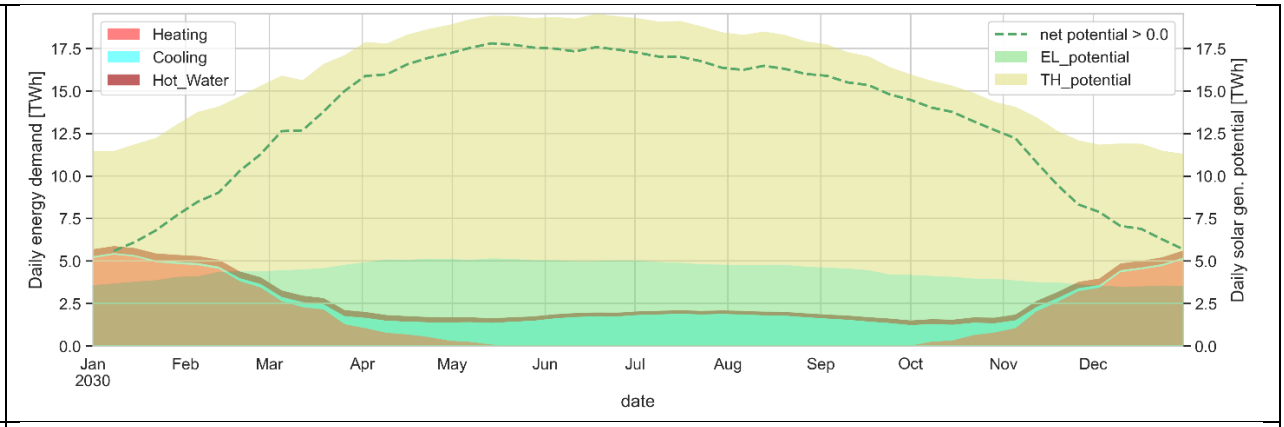
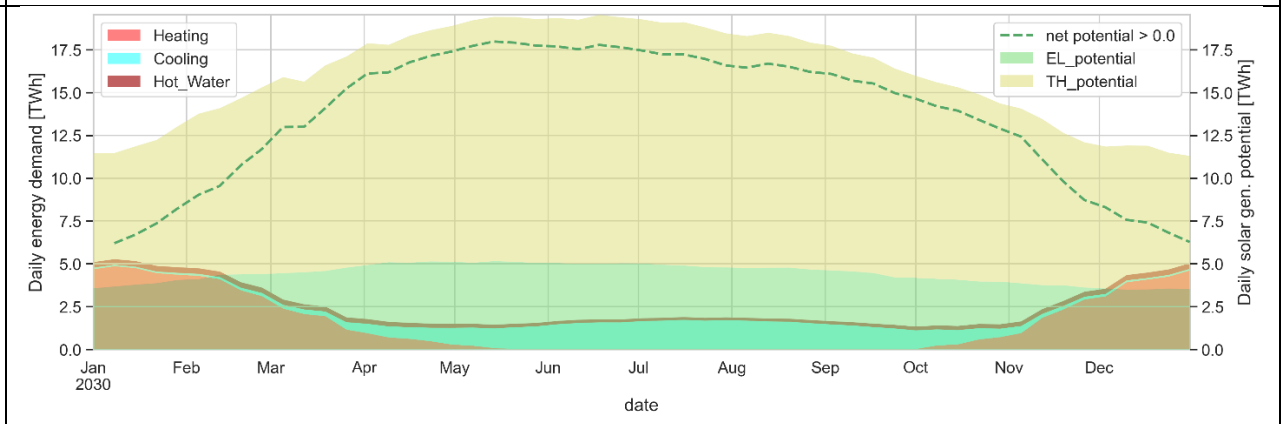
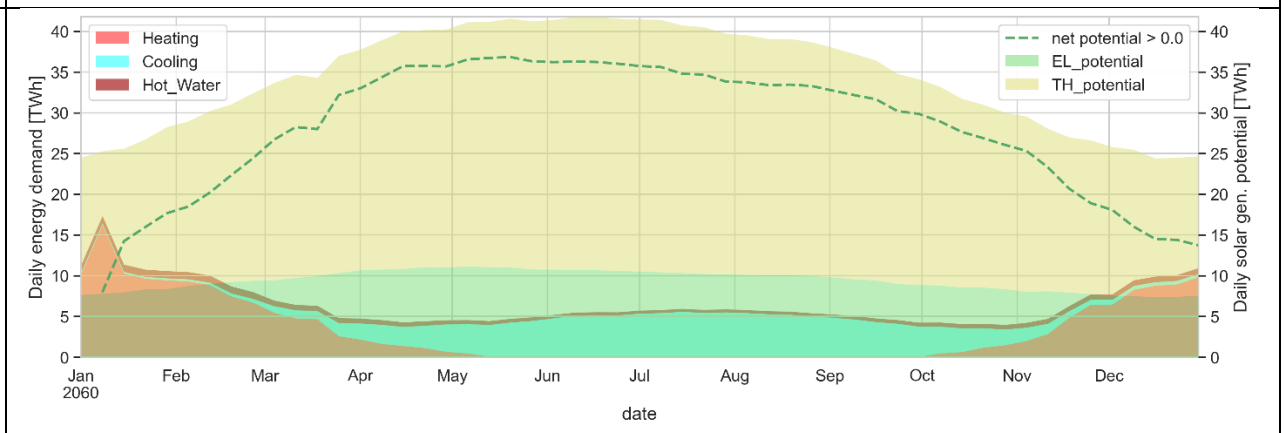
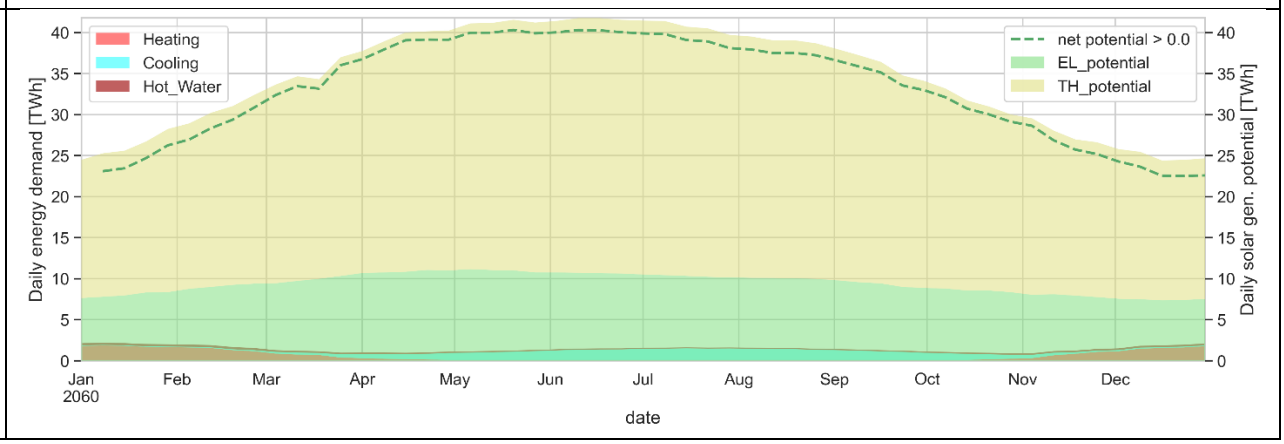
Frozen (2030)	

Deep (2030)	
Frozen (2060)	
Deep (2060)	

5.3.6 Middle East and Africa

Similar to the Latin American region, the building sector in the Middle East and Africa region can achieve throughout the year across different scenarios due to its high onsite solar energy production potential (Table 15). Due to receiving high solar radiation throughout the year, even with limited roof area availability, it is possible for the building sector to meet its annual and hourly energy demand by the onsite energy production.

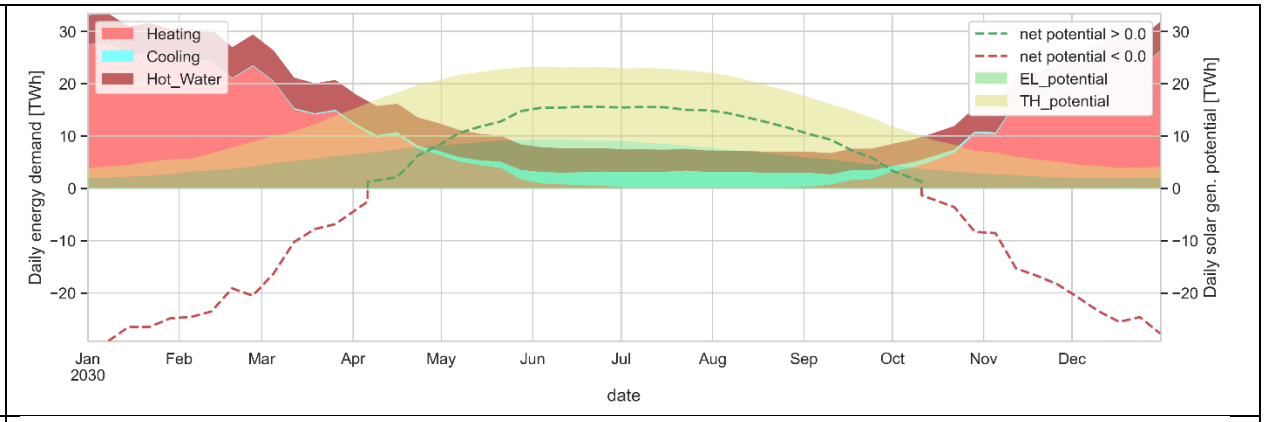
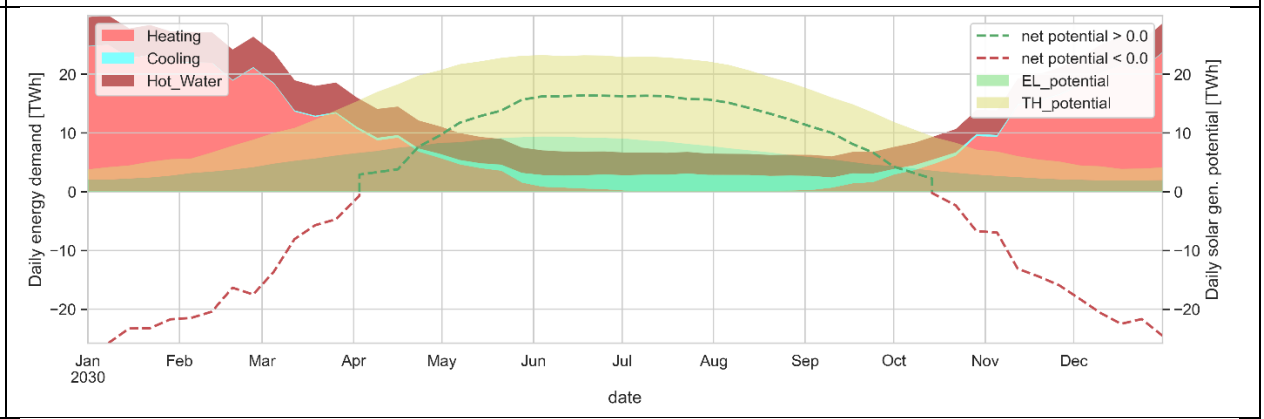
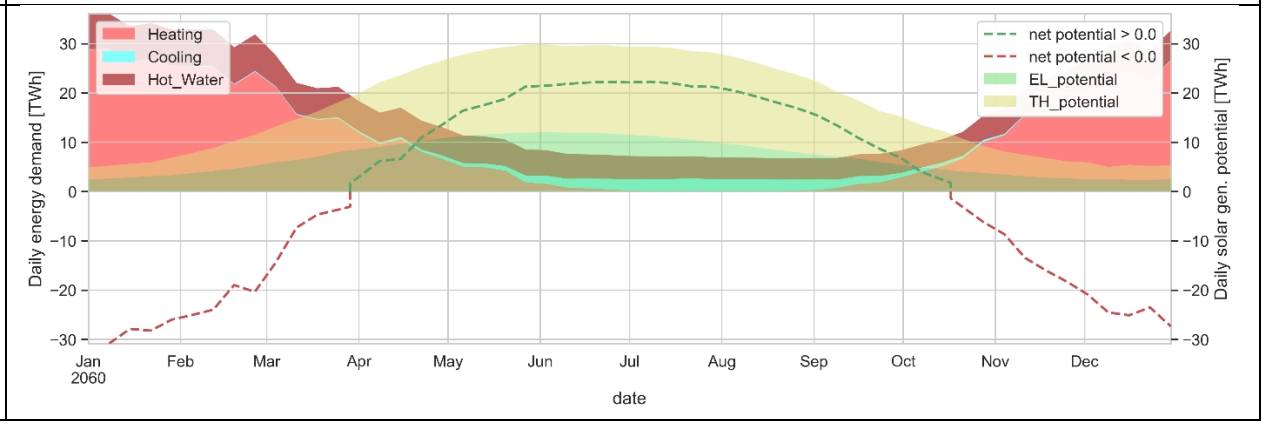
Table 15. Comparison of the HEB's hourly building energy demand and the BISE's technical potential of rooftop PV/T energy supply for Middle East and Africa

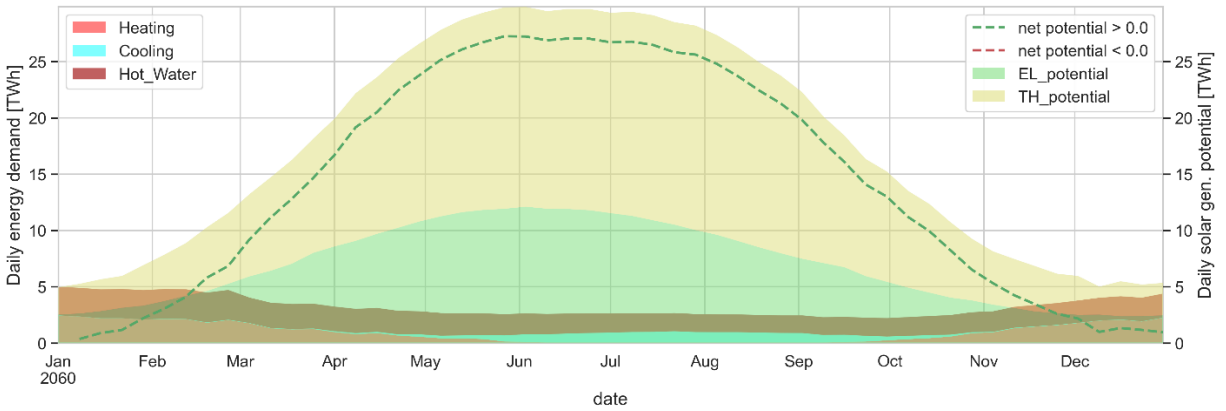
Frozen (2030)	
Deep (2030)	
Frozen (2060)	
Deep (2060)	

5.3.7 North America

Unlike Latin American region, the building sector in the North American region shows tremendous potential for the demand measures in order to achieve net-zero. More precisely, in this region, the building sector can only achieve net-zero by 2060 under Deep Efficiency scenario throughout the year when the demand measures are implemented. If the demand measures are not implemented, then on most of the days in a year, the building sector would not achieve net-zero (refer to Table 16).

Table 16. Comparison of the HEB's hourly building energy demand and the BISE's technical potential of rooftop PV/T energy supply for North America

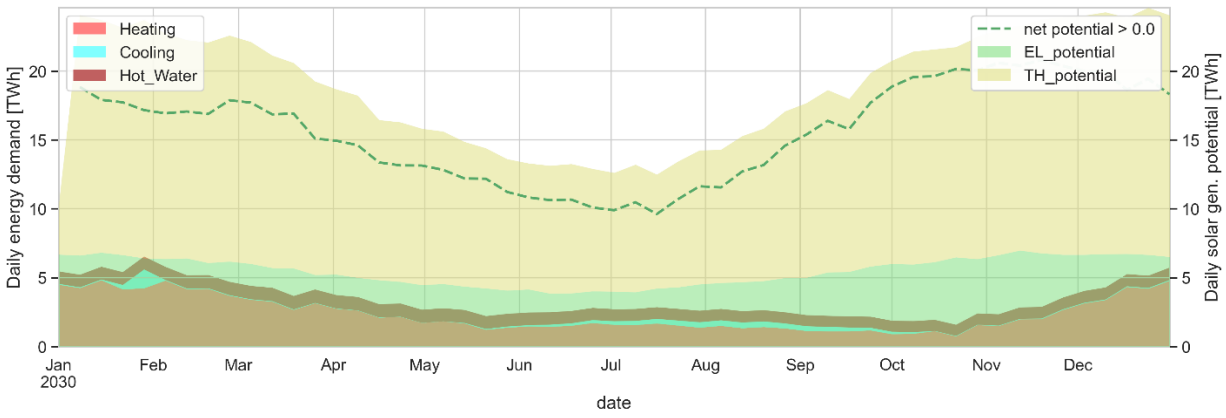
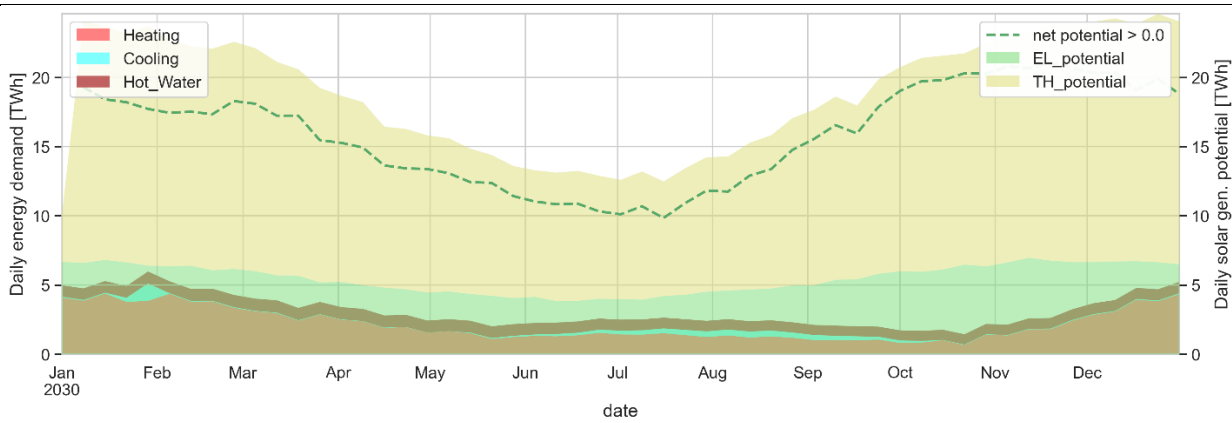
Frozen (2030)	
Deep (2030)	
Frozen (2060)	

Deep (2060)	

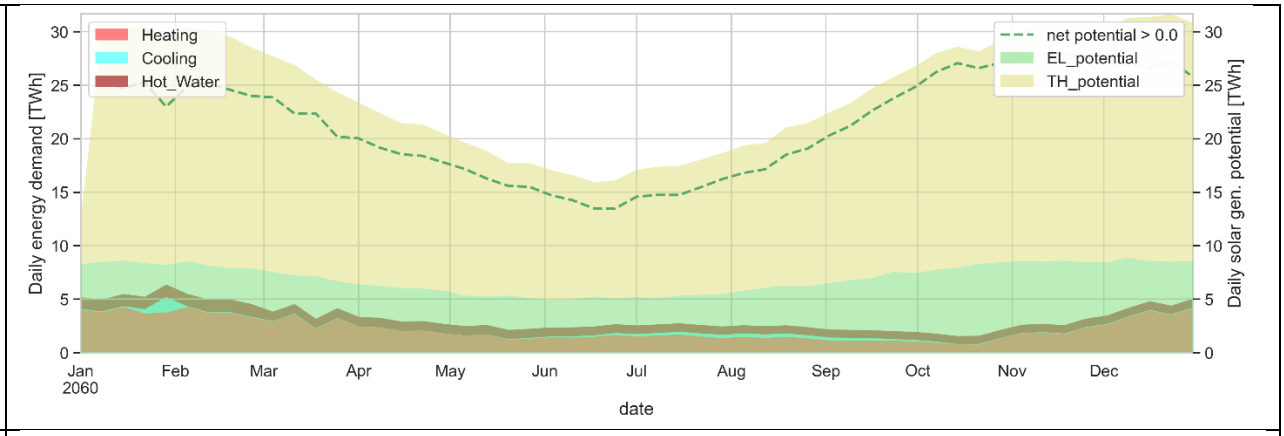
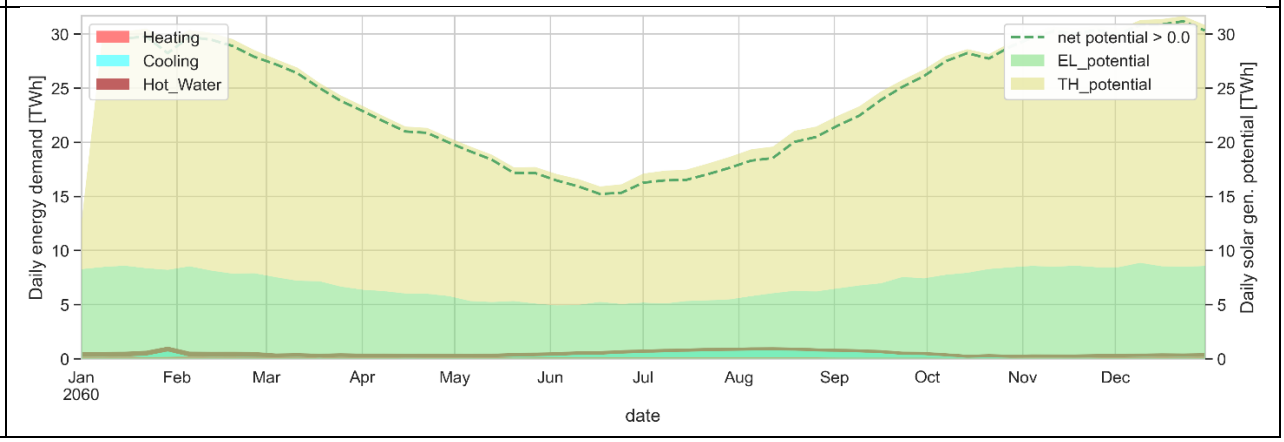
5.3.8 Pacific OECD

Due to the high solar radiation and roof area available for solar energy production, the building sector in Pacific OECD region can achieve net-zero throughout the year across all the scenarios (Table 17).

Table 17. Comparison of the HEB's hourly building energy demand and the BISE's technical potential of rooftop PV/T energy supply for Pacific OECD

Frozen (2030)	
Deep (2030)	

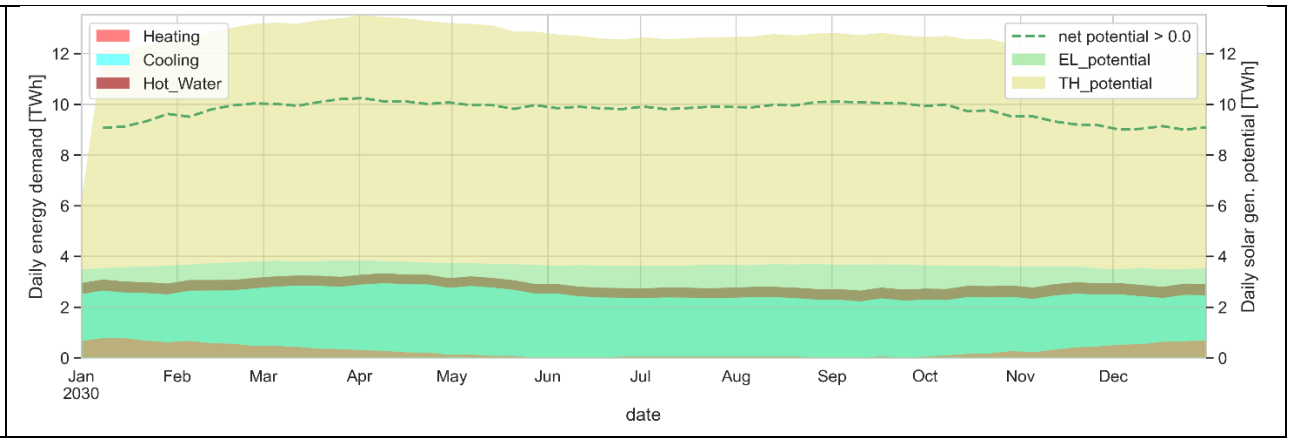
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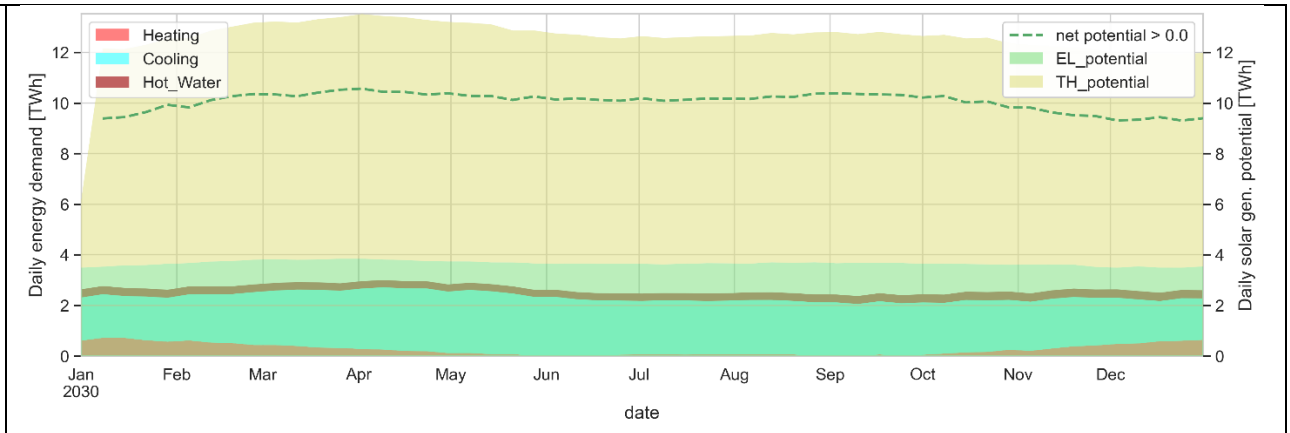
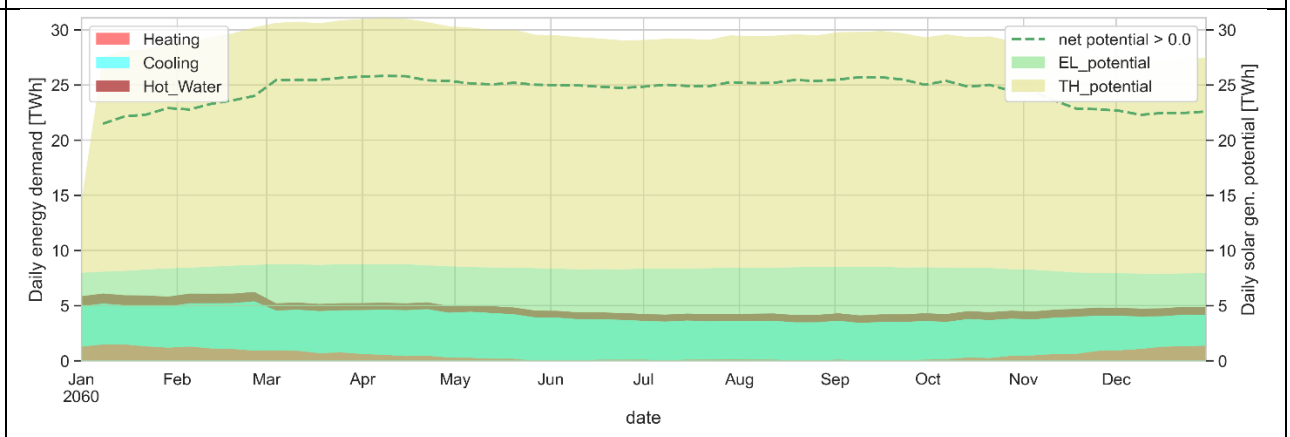
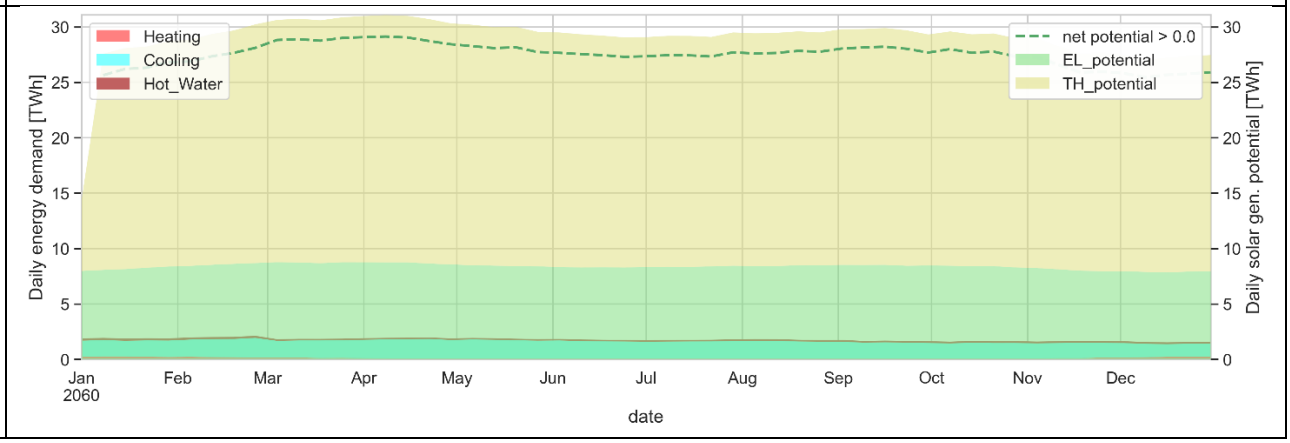
Frozen (2060)	
Deep (2060)	

5.3.9 Pacific Asia

Similar to Pacific OECD region, Pacific Asian region also achieves net-zero throughout the year across all the scenarios due to the high solar radiation and roof area available for solar energy production (Table 18).

Table 18. Comparison of the HEB's hourly building energy demand and the BISE's technical potential of rooftop PV/T energy supply for Pacific Asia

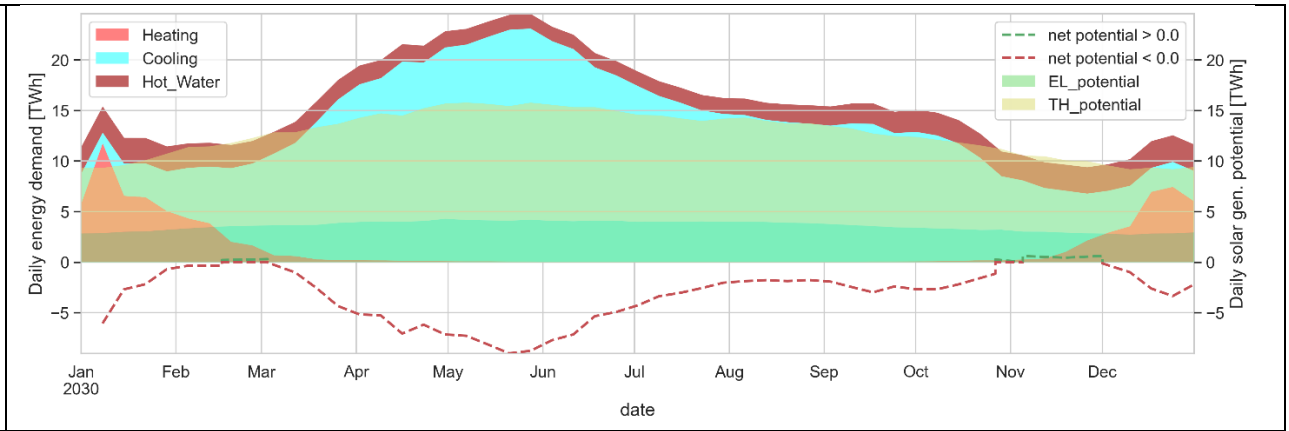
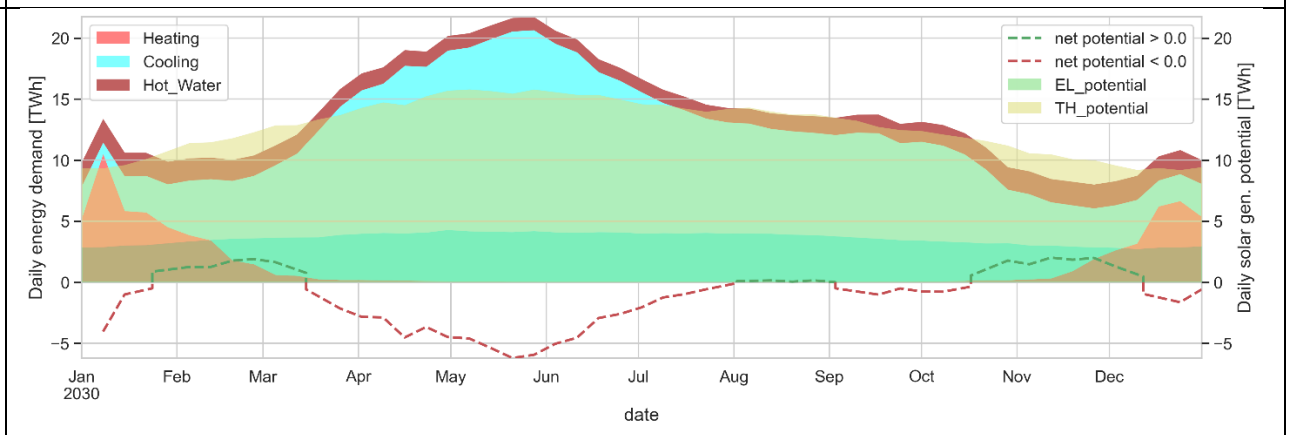
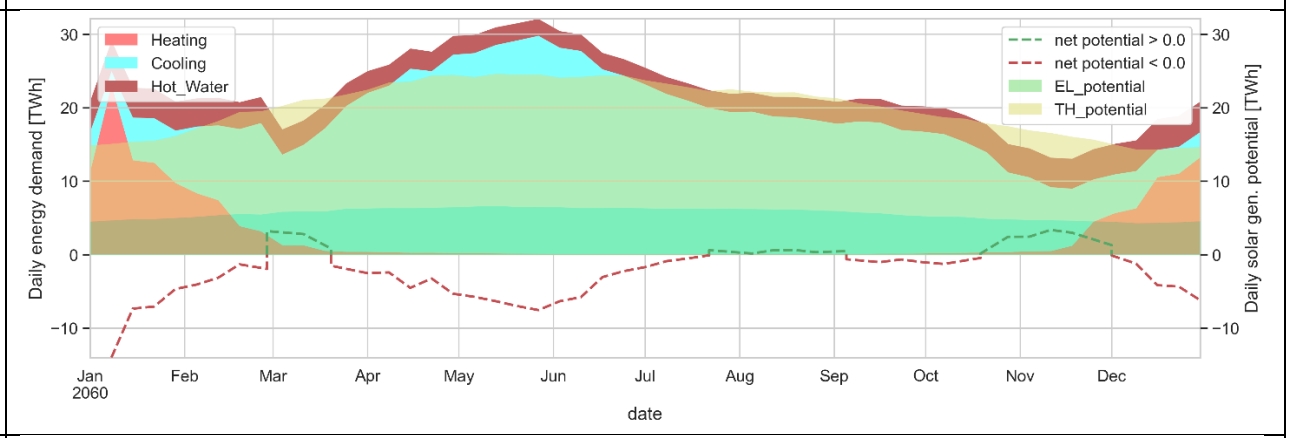
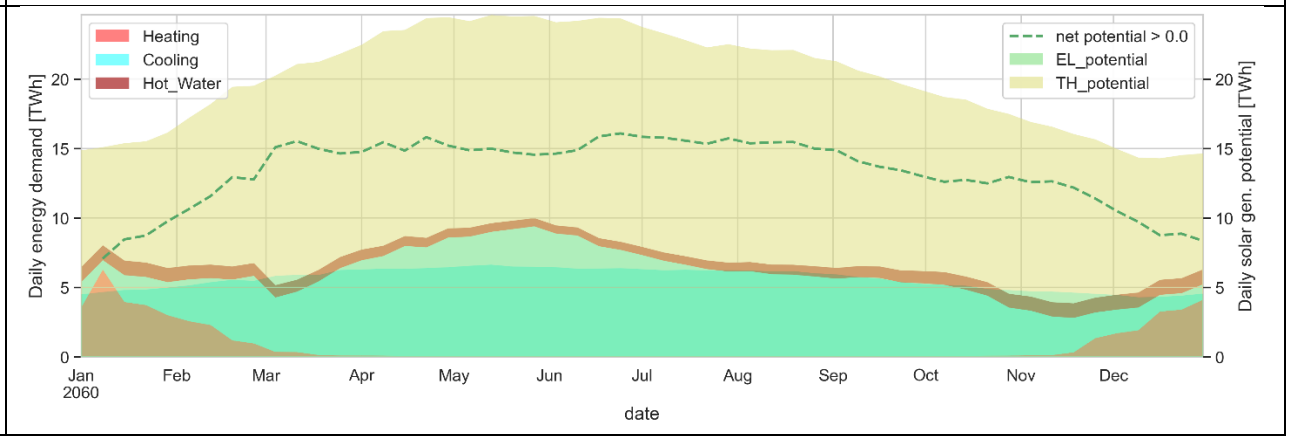
Frozen (2030)	

Deep (2030)	
Frozen (2060)	
Deep (2060)	

5.3.10 South Asia

The South Asian region shows substantial potential for the demand measures as net-zero can only be achieved in this region, if and only if the demand measures are implemented. In other words, only the Deep Efficiency scenario shows potential to achieve net-zero by 2060 when the demand, especially the demand for cooling is substantially reduced due to high-efficiency measures (Table 19).

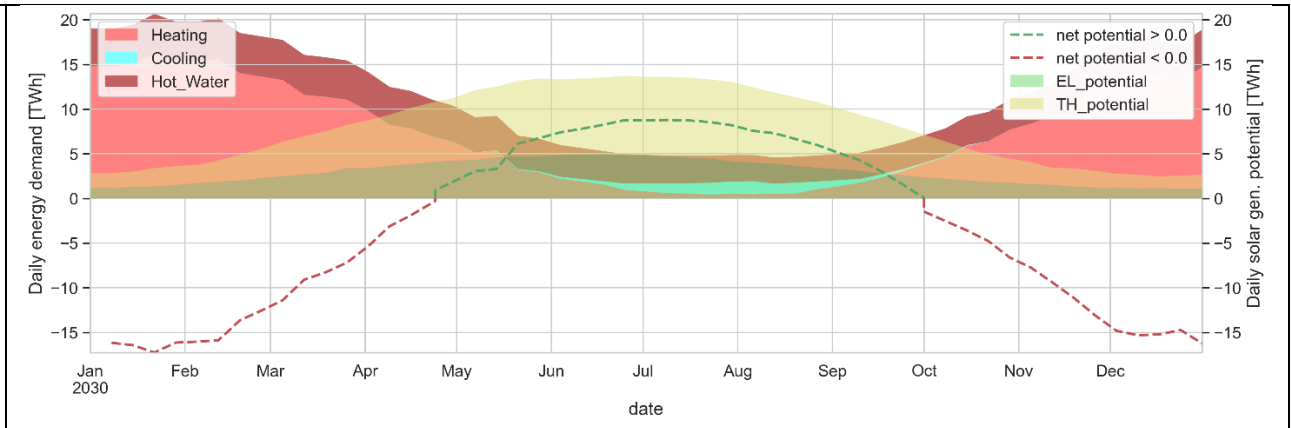
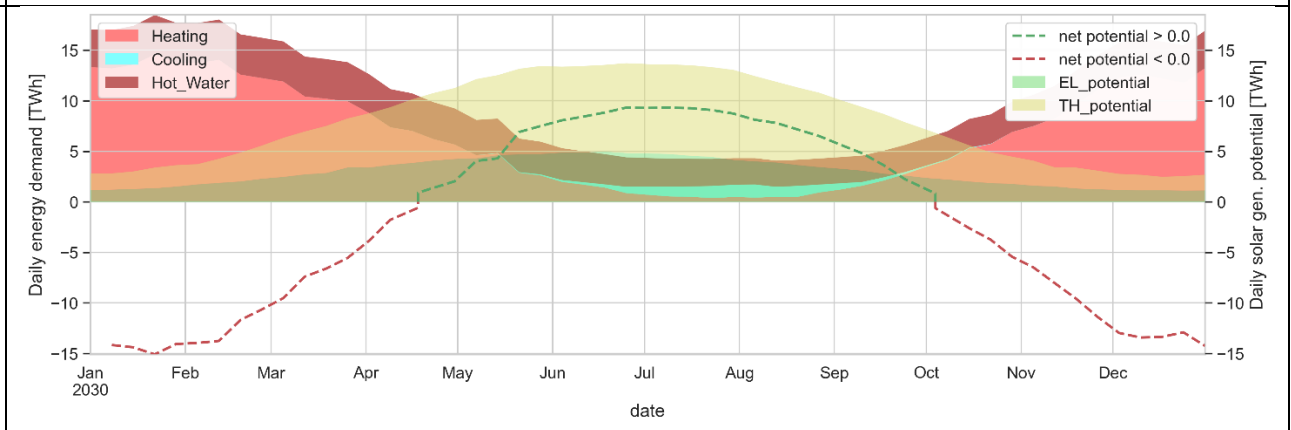
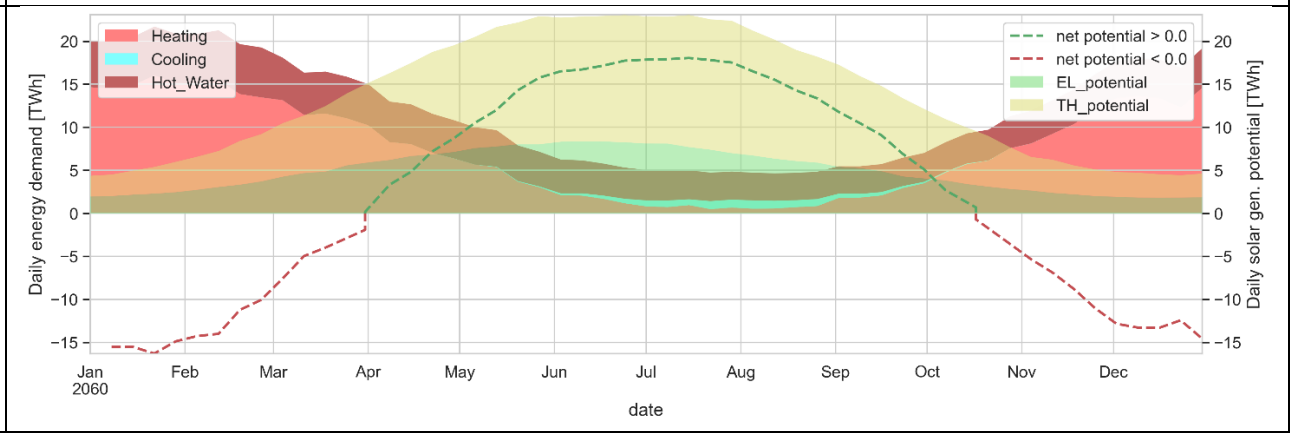
Table 19. Comparison of the HEB's hourly building energy demand and the BISE's technical potential of rooftop PV/T energy supply for South Asia

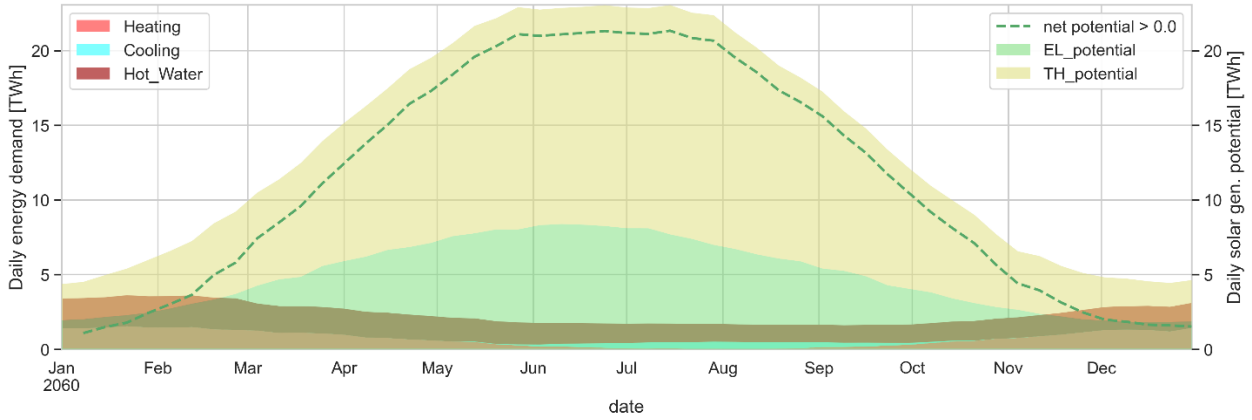
Frozen (2030)	
Deep (2030)	
Frozen (2060)	
Deep (2060)	

5.3.11 Western Europe

The Western European region is the perfect example to show the potential of demand reduction by presenting demand and onsite energy supply data for different scenarios (Table 20). Precisely, in this region, the net-zero potential can only be achieved only when demand measures are implemented, and if the demand measures are not followed then net-zero potential would be difficult to achieve. For instance, in the Frozen scenario, almost half of the year the demand would be much higher than the onsite solar production, whereas under the Deep Efficiency scenario, the solar energy production, would be much higher than the thermal energy demand throughout the year.

Table 20. Comparison of the HEB's hourly building energy demand and the BISE's technical potential of rooftop PV/T energy supply for Western Europe

Frozen (2030)	
Deep (2030)	
Frozen (2060)	

Deep (2060)	

6. Conclusion

As all demand and supply models, the databases and methodological assumptions used by the HEB and BISE have their inherent uncertainties that could impact the modelled outputs as well as the pace of the estimated energy transition. Therefore, a sensitivity analysis is conducted through the example of HEB model firstly to quantify the sensitivity of the model to its key parameters, secondly to determine an uncertainty range in the estimated energy demand and thirdly to showcase the significant dependence of future pathways of the building-related energy demand on the ambitiousness of policy measures being introduced over the forthcoming decades. Since the results of this analysis can be easily extended to all HEB scenarios, now only the case for the Deep Efficiency scenario is shown.

The importance of the accelerated retrofit rate in the model is to determine the share of the existing building being renovated to a better energy efficiency level. The HEB model in the Deep scenario assumes that the rate starts to increase from 1.4% in each investigated region/country from 2022. Then its growth is separated into developed and developing regions, with the corresponding target values of 3% and 1.5–1.6%. The year when the accelerated rate is achieved (shift year) is set to 2027, assuming a short period of market preparation. In the following years, the retrofit rate is considered to be fixed. By modifying the annual retrofit rates, the modelled global energy demand has very different final energy demand values by the end of the modeling period (Figure 37). As it is expected, lowering the retrofit rate results in higher energy demand by 2060. Precisely, if this rate is reduced to 50% or 75% of its default value, the modelled demand rises by 25% and 7% to its baseline value. Reversely, the 25% and 50% increase in the renovation rate leads to 5% and 10% drop in energy demand. In absolute terms, the uncertainty between the different cases can be as high as 4.4 PWh, which is 34% of the total energy demand estimated by the Deep Efficiency scenario.

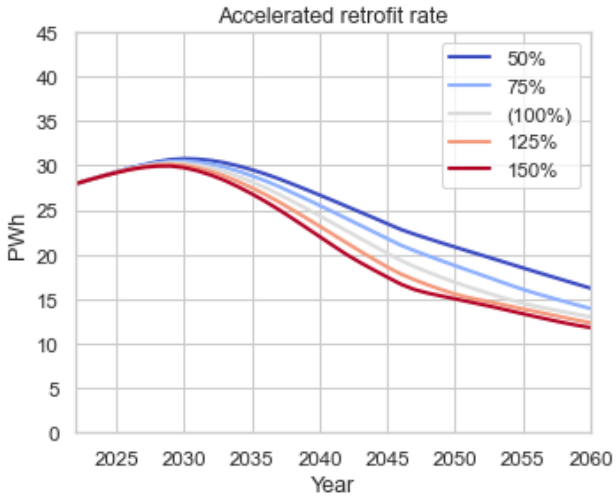


Figure 37. Sensitivity of building-related global energy demand to the accelerated retrofit rate in the Deep Efficiency scenario

Figure 38 illustrates different energy demand curves simulated with multiple dates for the introduction of advanced policies. In the Deep Efficiency scenario by default, 2027 is considered to be the first year when buildings with very ambitious energy performance measures appear in the building stock of the majority of the regions. Relative to this year, a five-year, ten-year, and twenty-year delay, as well as an urgent introduction (5 years sooner) are now examined. It is a rule-of-thumb that the later advanced buildings become widespread, the more risk is taken to push down energy demand to an expected low level. If the delay is set to be 5-year, 10-year and 20-year, the estimated increases in the demand values to the baseline level are 32, 72 and 141% by 2060, respectively. On the other hand, if advanced buildings would spread sooner, the reduction potential is estimated to be 26%. It can be concluded that the sensitivity of the HEB's energy demand outcomes seem to be very strong to the advanced policies. In fact, the highest uncertainty is generated by this assumption among the analyzed input parameters, which turned out to be in a range around 22 PWh.

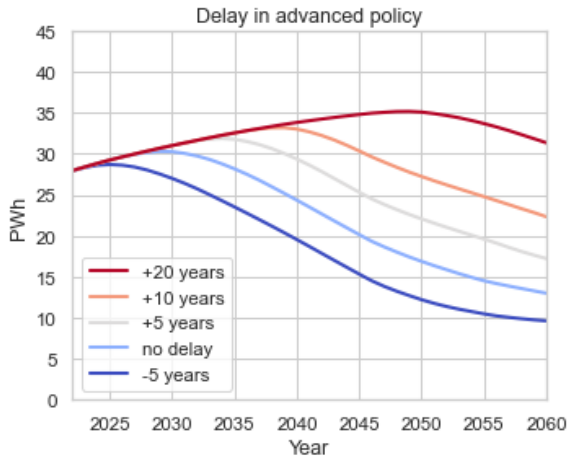


Figure 38. Sensitivity of building-related global energy demand to the appearence of high energy performace buildings in the Deep Efficiency scenario

The forthcoming values of energy intensity for different end-use activities (e.g., space heating, cooling, hot water production, lighting, etc.) must also be significantly limit relative to their current levels, for

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instance, by applying energy efficient, green solutions when it comes to energy consumption. The investigated scenario assumes significant spread of energy efficient buildings throughout the modeling period, although the efficiency that can be reached by the entire building stock is highly dubious. To scrutinize the corresponding uncertainty, Figure 39 summarizes results for different energy intensity cases, by changing the default mean HEB input value by 50 to 250%. It is seen that the lowest demand occurs if the assumed energy intensity is half of the reference value. Then the reference energy demand is pushed down by 62% by 2060. In any other sensitivity clusters, higher final energy needs are found in the experiments. By indicating non-linear relationship between the variables, growths of 50%, 100% and 150% in the energy intensity leads to energy demand increments of 18%, 35% and 53%, respectively. Consequently, the energy intensity can be considered the second most important parameter to which the HEB model is the most sensitive. In this concrete example, the uncertainty has a range of 9.2 PWh, emphasizing the energy intensity as a major factor in future energy transition of the building sector.

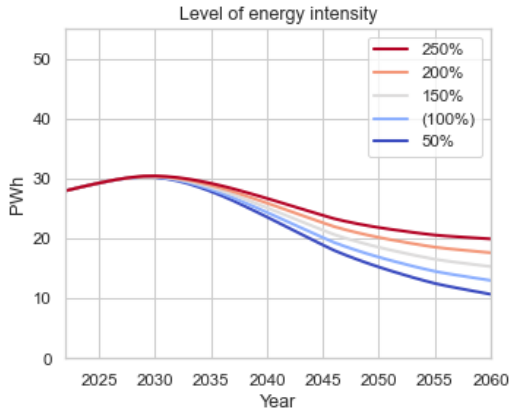


Figure 39. Sensitivity of building-related global energy demand to the energy intensity in the Deep Efficiency scenario

Despite the uncertainties that any modelling analysis might include, it can be clearly concluded on the basis of the results present in the previous sections that the reduction of energy demand and greenhouse gas emission associated with the building sector would play pivotal role to keep the global warming potential well below 1.5 degrees. Especially, COVID pandemic and then Ukraine-Russia war show the importance of demand side measures in achieving the net-zero transition. 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. The empirical evidence here would help us understand the full potential of the building in terms of reducing energy demand and producing onsite energy.

By analyzing the annual and hourly energy demand and supply profiles of the global and regional building sector, this study illustrates the potential for net-zero building sector. The study's conclusions demonstrate that net-zero potentiality can be attained in the future with the implementation of best building practices such as deep-energy renovation, and high-efficiency building construction across the world. The assumption-heavy nature of this scenario to high efficiency or net-zero demands robust policy backing, especially for supporting deep-energy renovation, and making building codes stringent to ensure new construction of high-efficiency buildings. Because, if we do not follow deep-renovation and high-efficiency constructions globally then the total thermal energy demand of the building sector could increase up to 80% by 2060 compared to the level in 2022 or even if the current policy scenarios

are continued (Moderate Efficiency scenario). Furthermore, if the best building practices are followed then globally 130% of energy could be 'locked-in' between 2022 and 2060.

However, it is important to understand that deep-energy renovation is often expensive and hence, it may not be affordable to the lower income group. Therefore, some protective measures such as easy deep renovation loan by the government, or some form of subsidy to accelerate the deep renovation is required. Because, if most of the buildings settle for shallow renovation, then there is a potential risk of locking in substantially the energy reduction, precisely, 130% of energy could be 'locked-in' between 2022-2060 which would hamper the progress towards achieving net-zero target. Furthermore, the deep-renovation and passive house building constructions also generate several major co-benefits which includes improvement of health, productivity, improving public budget and GDP (Chatterjee and Ürge-Vorsatz, 2021). These co-benefits should also be considered while assessing the 'cost' of deep-energy renovation.

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References

Arshad, M., Ma, X., Yin, J., Ullah, W., Liu, M., Ullah, I., 2021. Performance evaluation of ERA-5, JRA-55, MERRA-2, and CFS-2 reanalysis datasets, over diverse climate regions of Pakistan. Weather Clim. Extrem. 33, 100373. https://doi.org/10.1016/j.wace.2021.100373

Baum, S., Horton, S., Choy, D.L., Gleeson, B., 2009. Climate change, health impacts and urban adaptability : Case study of Gold Coast City.

Belussi, L., Barozzi, B., Bellazzi, A., Danza, L., Devitofrancesco, A., Fanciulli, C., Ghellere, M., Guazzi, G., Meroni, I., Salamone, F., Scamoni, F., Scrosati, C., 2019. A review of performance of zero energy buildings and energy efficiency solutions. J. Build. Eng. 25, 100772. https://doi.org/10.1016/j.jobe.2019.100772

Bhatnagar, M., Mathur, J., Garg, V., 2018. Determining base temperature for heating and cooling degree-days for India. J. Build. Eng. 18, 270–280. https://doi.org/10.1016/j.jobe.2018.03.020

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

Carro-Calvo, L., Ordóñez, C., García-Herrera, R., Schnell, J.L., 2017. Spatial clustering and meteorological drivers of summer ozone in Europe. Atmos. Environ. 167, 496–510. https://doi.org/10.1016/j.atmosenv.2017.08.050

Chatterjee, S., Kiss, B., Ürge-Vorsatz, D., Teske, S., 2022a. Decarbonisation Pathways for Buildings, in: Achieving the Paris Climate Agreement Goals. Springer International Publishing, Cham, pp. 161–185. https://doi.org/10.1007/978-3-030-99177-7_7

Chatterjee, S., Molnár, G., Ürge-Vorsatz, D., Kiss, B., Topál, D., 2023. Climate neutral EU building sector - A reality or dream? Energy. (Before submission)

Chatterjee, S., Stavrakas, V., Oreggioni, G., Süsser, D., Staffell, I., Lilliestam, J., Molnar, G., Flamos, A., Ürge-Vorsatz, D., 2022b. Existing tools, user needs and required model adjustments for energy demand modelling of a carbon-neutral Europe. Energy Res. Soc. Sci. 90, 102662. https://doi.org/10.1016/j.erss.2022.102662

Chatterjee, S., Ürge-Vorsatz, D., 2021. Measuring the productivity impacts of energy-efficiency: The case of high-efficiency buildings. J. Clean. Prod. 318, 128535. https://doi.org/10.1016/j.jclepro.2021.128535

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. Chang. 8, 268–271. https://doi.org/10.1038/s41558-018-0121-1

Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D.P., Edelenbosch, O., Heijungs, R., 2020. Modelling global material stocks and flows for residential and service sector buildings towards 2050. J. Clean. Prod. 245, 118658. https://doi.org/10.1016/j.jclepro.2019.118658

Deroubaix, A., Labuhn, I., Camredon, M., Gaubert, B., Monerie, P.A., Popp, M., Ramarohetra, J., Ruprich-Robert, Y., Silvers, L.G., Siour, G., 2021. Large uncertainties in trends of energy demand

for heating and cooling under climate change. Nat. Commun. 12, 6–13. https://doi.org/10.1038/s41467-021-25504-8

Enerdata, 2022. World Energy & Climate Statistics - Yearbook 2022 [WWW Document]. URL https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html

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

Gielen, D., Boshell, F., Saygin, D., Bazilian, M.D., Wagner, N., Gorini, R., 2019. The role of renewable energy in the global energy transformation. Energy Strateg. Rev. 24, 38–50. https://doi.org/10.1016/j.esr.2019.01.006

González-Torres, M., Pérez-Lombard, L., Coronel, J.F., Maestre, I.R., Yan, D., 2022. A review on buildings energy information: Trends, end-uses, fuels and drivers. Energy Reports 8, 626–637. https://doi.org/10.1016/j.egyr.2021.11.280

Grove-Smith, J., Aydin, V., Feist, W., Schnieders, J., Thomas, S., 2018. Standards and policies for very high energy efficiency in the urban building sector towards reaching the 1.5°C target. Curr. Opin. Environ. Sustain. 30, 103–114. https://doi.org/10.1016/j.cosust.2018.04.006

Güneralp, B., Zhou, Y., Ürge-Vorsatz, D., Gupta, M., Yu, S., Patel, P.L., Fragkias, M., Li, X., Seto, K.C., 2017. Global scenarios of urban density and its impacts on building energy use through 2050. Proc. Natl. Acad. Sci. U. S. A. 114, 8945–8950. https://doi.org/10.1073/pnas.1606035114

Hosseini, S.E., 2022. Transition away from fossil fuels toward renewables: lessons from Russia-Ukraine crisis. Futur. Energy 1, 2–5. https://doi.org/10.55670/fpll.fuen.1.1.8

IEA, 2022a. National Reliance on Russian Fossil Fuel Imports. Paris.

IEA, 2022b. Energy Fact Sheet: Why does Russian oil and gas matter? [WWW Document]. URL https://www.iea.org/articles/energy-fact-sheet-why-does-russian-oil-and-gas-matter

IEA, 2022c. World Energy Outlook- WEO2022 524.

IEA, 2022d. Tracking Buildings 2022. https://www.iea.org/reports/tracking-buildings-2020

IEA, 2022e. Energy consumption in buildings by fuel in the Net Zero Scenario, 2010-2030 [WWW Document]. URL https://www.iea.org/data-and-statistics/charts/energy-consumption-in-buildings-by-fuel-in-the-net-zero-scenario-2010-2030

IEA, 2022f. Shares of residential energy consumption by end use ub selected IEA countries, 2019 [WWW Document]. URL https://www.iea.org/data-and-statistics/charts/shares-of-residential-energy-consumption-by-end-use-in-selected-iea-countries-2019

IEA, 2022g. Appliances and Equipment. https://www.iea.org/reports/appliances-and-equipment

IEA, 2022h. Space Cooling. https://www.iea.org/reports/space-cooling

IEA, 2021. Greenhouse Gas Emissions from Energy Data Explorer. https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer

IEA, 2019. The Critical Role of Buildings. https://www.iea.org/reports/the-critical-role-of-buildings

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

Jiang, P., Fan, Y. Van, Klemeš, J.J., 2021. Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities. Appl. Energy 285. https://doi.org/10.1016/j.apenergy.2021.116441

Jurasz, J.K., Dąbek, P.B., Campana, P.E., 2020. Can a city reach energy self-sufficiency by means of rooftop photovoltaics? Case study from Poland. J. Clean. Prod. 245. https://doi.org/10.1016/j.jclepro.2019.118813

Keller, J.D., Wahl, S., 2021. Representation of Climate in Reanalyses: An Intercomparison for Europe and North America. J. Clim. 34, 1667–1684. https://doi.org/10.1175/JCLI-D-20-0609.1

Kim, H.-G., Kim, J.-Y., Kang, Y.-H., 2018. Comparative Evaluation of the Third-Generation Reanalysis Data for Wind Resource Assessment of the Southwestern Offshore in South Korea. Atmosphere (Basel). 9, 73. https://doi.org/10.3390/atmos9020073

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

Lämmle, M., Herrando, M., Ryan, G., 2020. Basic concepts of PVT collector technologies, applications and markets. https://doi.org/10.18777/ieashc-task60-2020-0002

Lee, K., Baek, H.-J., Cho, C., 2014. The Estimation of Base Temperature for Heating and Cooling Degree-Days for South Korea. J. Appl. Meteorol. Climatol. 53, 300–309. https://doi.org/10.1175/JAMC-D-13-0220.1

Madhu, K., Pauliuk, S., Dhathri, S., Creutzig, F., 2021. Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment. Nat. Energy 6, 1035–1044. https://doi.org/10.1038/s41560-021-00922-6

Masson-Delmotte, V.. P.Z.H.-O.P.D.R.J.S.P.R.S.A.P.W.M.-O.C.P.R.P.S.C.J.B.R.M.Y.C.X.Z.M.I.G.E.L.T.M.M.T. and T.W. (eds. ., 2018. Summary for Policymakers. In Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty (. Glob. Warm. 1.5°C 1–24.

Masterson, J., Richardson, F.A., 1979. Humidex, A Method of Quantifying Human Discomfort Due to Excessive Heat and Humidity., Downsview, Ontario: Environment Canada.

Mellor, A., Alonso Alvarez, D., Guarracino, I., Ramos, A., Riverola Lacasta, A., Ferre Llin, L., Murrell, A.J., Paul, D.J., Chemisana, D., Markides, C.N., Ekins-Daukes, N.J., 2018. Roadmap for the next-generation of hybrid photovoltaic-thermal solar energy collectors. Sol. Energy 174, 386–398. https://doi.org/10.1016/j.solener.2018.09.004

Meng, Q., Mourshed, M., 2017. Degree-day based non-domestic building energy analytics and modelling should use building and type specific base temperatures. Energy Build. 155, 260–268. https://doi.org/10.1016/j.enbuild.2017.09.034

Molnár, G., Cabeza, L.F., Chatterjee, S., Ürge-Vorsatz, D., 2023. Modeling the roof integrated solar energy production in the EU. Energy. (Before submission)

Molnár, G., Ürge-Vorsatz, D., Chatterjee, S., 2022. Estimating the global technical potential of building-integrated solar energy production using a high-resolution geospatial model. J. Clean. Prod. 375. https://doi.org/10.1016/j.jclepro.2022.134133

Newell, R., Raimi, D., Villanueva, S., Prest, B., others, 2021. Global energy outlook 2021: pathways from Paris. Resour. Futur. Rep. 11–21.

Patt, A., van Vliet, O., Lilliestam, J., Pfenninger, S., 2019. Will policies to promote energy efficiency help or hinder achieving a 1.5 °C climate target? Energy Effic. 12, 551–565. https://doi.org/10.1007/s12053-018-9715-8

Petrichenko, K., 2014. Net-Zero Energy Buildings: Global and Regional Perspectives. Central European University.

Petrichenko, K., Ürge-Vorsatz, D., Cabeza, L.F., 2019. Modeling global and regional potentials for building-integrated solar energy generation. Energy Build. 198, 329–339. https://doi.org/10.1016/j.enbuild.2019.06.024

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

Ritchie, H., Rosser, M., Rossado, P., 2022. Energy [WWW Document]. URL https://ourworldindata.org/energy

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

Rosenow, J., Kern, F., Rogge, K., 2017. The need for comprehensive and well targeted instrument mixes to stimulate energy transitions: The case of energy efficiency policy. Energy Res. Soc. Sci. 33, 95–104. https://doi.org/10.1016/j.erss.2017.09.013

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

Schulzweida, U., 2019. CDO User Guide 1–206. https://code.mpimet.mpg.de/projects/cdo/embedded/cdo.pdf

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

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

Spinoni, J., Vogt, J. V., Barbosa, P., Dosio, A., McCormick, N., Bigano, A., Füssel, H.M., 2018. Changes of heating and cooling degree-days in Europe from 1981 to 2100. Int. J. Climatol. 38, e191–e208. https://doi.org/10.1002/joc.5362

Sudhakar, K., Winderla, M., Priya, S.S., 2019. Net-zero building designs in hot and humid climates: A state-of-art. Case Stud. Therm. Eng. 13. https://doi.org/10.1016/j.csite.2019.100400

Syakur, M.A., Khotimah, B.K., Rochman, E.M.S., Satoto, B.D., 2018. Integration K-Means Clustering Method and Elbow Method For Identification of The Best Customer Profile Cluster. IOP Conf. Ser. Mater. Sci. Eng. 336, 012017. https://doi.org/10.1088/1757-899X/336/1/012017

Taleb, S., Yeretzian, A., Jabr, R.A., Hajj, H., 2020. Optimization of building form to reduce incident solar radiation. J. Build. Eng. 28, 101025. https://doi.org/10.1016/j.jobe.2019.101025

Teske, S., Orbe, J.G., Assaf, J., Chatterjee, S., 2022. Methodology. Achieving the Paris Climate Agreement Goals pp 25–59 https://doi.org/10.1007/978-3-030-99177-7_3

UN, 2018. World Urbanization Prospects 2018, Department of Economic and Social Affairs. World Population Prospects 2018.

UNEP, 2023. Cities and climate change [WWW Document]. URL https://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities/cities-and-climate-change

UNEP, 2022. 2022 Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector. Nairobi.

Urge-Vorsatz, D., 2012. Best Practice Policies for Low Carbon & Energy Buildings Best Practice Policies for Low Carbon & Energy Buildings.

Ürge-Vorsatz, D., Cabeza, L.F., Serrano, S., Barreneche, C., Petrichenko, K., 2015. Heating and cooling energy trends and drivers in buildings. Renew. Sustain. Energy Rev. 41, 85–98. https://doi.org/10.1016/j.rser.2014.08.039

Ürge-Vorsatz, D., Chatterjee, S., Cabeza, L.F., Molnár, G., 2023a. Global and regional estimation and evaluation of suitable roof area for solar and green roof applications. Energy. (Before submission)

Ürge-Vorsatz, D., Chatterjee, S., Molnár, G., Cabeza, L.F., 2023b. Buildings floor area global and regional worldwide estimations. Energy. (Before submission)

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

Walch, A., Castello, R., Mohajeri, N., Scartezzini, J.L., 2020. Big data mining for the estimation of hourly rooftop photovoltaic potential and its uncertainty. Appl. Energy 262, 114404. https://doi.org/10.1016/j.apenergy.2019.114404

Wang, H., Chen, Q., 2014. Impact of climate change heating and cooling energy use in buildings in the United States. Energy Build. 82, 428–436. https://doi.org/10.1016/j.enbuild.2014.07.034

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

World Bank, 2022. Commodity markets Outlook.The Impact of the War in Ukraine on Commodity Markets.

Yang, T., Athienitis, A.K., 2016. A review of research and developments of building-integrated photovoltaic/thermal (BIPV/T) systems. Renew. Sustain. Energy Rev. 66, 886–912. https://doi.org/10.1016/j.rser.2016.07.011

Zakeri, B., Paulavets, K., Barreto-Gomez, L., Echeverri, L.G., Pachauri, S., Boza-Kiss, B., Zimm, C., Rogelj, J., Creutzig, F., Ürge-Vorsatz, D., Victor, D.G., Bazilian, M.D., Fritz, S., Gielen, D., McCollum, D.L., Srivastava, L., Hunt, J.D., Pouya, S., 2022. Pandemic, War, and Global Energy Transitions. Energies 15, 6114. https://doi.org/10.3390/en15176114

Zhou, X.Y., Lu, G., Xu, Z., Yan, X., Khu, S.T., Yang, J., Zhao, J., 2023. Influence of Russia-Ukraine War on the Global Energy and Food Security. Resour. Conserv. Recycl. 188, 106657. https://doi.org/10.1016/j.resconrec.2022.106657

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EDITS
Energy Demand changes Induced by Technological and Social innovations

WP2 Data deliverable

Identifying key data gaps in description of Low Energy Demand Pathways

EDITS
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This document describes the progress made in the EDITS Data work package (WP2) in identifying key data gaps that need to be overcome to strengthen the description of Low Energy Demand (LED) Pathways. It contains a general description of the work package aims and goals, and the role that identifying the key data gaps plays in achieving those goals. The document describes the progress made in 2022 in two activities contributing to identifying data gaps and the foreseen next steps in the coming year.

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1 Introduction
2 EDITS WP2 Literature review data gaps
3 EDITS WP2 Meta database: connecting availability & needs

1. Introduction

The literature on demand side solutions to limit climate change has been rapidly growing, which is reflected also by the "Demand, Services and Social Aspects of Mitigation" chapter in the recently published sixth assessment Working Group 3 report of the IPCC. The inadequacy of current emissions reductions efforts has made the world more dependent on demand side changes to remain within the increasingly tighter carbon budget associated with limiting global warming to 1.5 ºC or 2 ºC. Demand side changes such as lifestyle choices, consumer technology choices, efficient behaviour can support near term climate change mitigation and decrease reliance on carbon dioxide removal (CDR) technologies in the long term. The feasibility of large scale application of CDR is frequently questioned. For example the application of biofuels and carbon capture and storage will require large amounts of land and water, impacting food production, water scarcity and biodiversity. Demand side solutions, as a result support staying within the planetary boundaries and entail less environmental risks than many supply side solutions.

Traditionally, however, many global model studies have been focussing on supply side mitigation - although this is recently changing. A key reason for this is also that there is a high level of diversity and complexity in the demand sectors that is difficult to capture in the broad perspective of these models. There is a trade-off between including many functions, types of users and technologies, that could become detrimental in their meaning over a century time frame and comes at the cost of transparency, or having a more simple representation. The simple representation could capture general behaviour but provides less insights into tangible measures which is, given the reliance on demand side measures to mitigate climate change, becoming increasingly important to understand.

A barrier in the representation of detailed demand side dynamics is the availability of data. Sectoral data on consumer lifestyle, choice, technologies and behaviour is needed which is heterogeneous and dependent on local conditions. For example, while reaching zero emissions in the building sector is technically possible, the profitability of investments depends on local circumstances, such as the age of the buildings, building archetype and conditions that are site- specific. Moreover the affordability will depend on household circumstances, such as access to capital/finance, household structure and whether the house is rented or bought. This shows the different dimensions, the complexity and heterogeneity of the data that need to be considered, which makes it challenging to collect and to analyse.

The IPCC's Special Report on Global Warming of 1.5°C (SR1.5), explores four stylised scenarios towards stabilising global warming at 1.5°C. One of these four scenarios, LED-19, analyses the scope of demand-side solutions. The scenario shows that global final energy demand can be reduced by 2050 to levels around 40% lower than today, despite rises in population, income and activity. Reduced energy demand drastically improves the feasibility of the supply-side- transformation, and allows to meet the 1.5 °C climate target as well as many sustainable development goals, without relying on negative emission technologies. The scenario provides a clear description of a low energy demand future and its advantages. The next step is however to understand how to get there and the dynamics behind such a transition.

The aim of this EDITS WP2 activity is therefore to identify the data gaps that need to be overcome to strengthen the description of low energy demand pathways and support the next IPCC assessment report in this challenge. In the EDITS Data work package this is done by two separate activities that both search for the data gaps at the cross section of data needs and data availability. The first activity is a structured analysis of the literature based on the Activity-Structure-Intensity framework, a commonly used framework in the field of demand side scenarios. The second activity builds on the EDITs community experience and knowledge, using the developed meta database as a data sharing platform to exchange information about data needs and availability.

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 sustainable 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.

The two activities have contributed to both goals. In this report we discuss the two activities in particular in relation to understanding the key data gaps.

2. EDITS WP2 Literature review data gaps

The data working group is collectively performing a systematic literature review to map the availability of demand data required to better represent low energy demand pathways. The review builds on the work done during the writing of the AR6 "Demand, Services and Social Aspects of Mitigation" chapter. The starting point is the Avoid -Shift-Improve Framework, with Avoid referring to Avoiding the need/demand for energy service, Shift to Shifting to different energy service, and Improve to Improving the energy efficiency or lowering the carbon intensity of energy services. The framework

allows to differentiate between different demand side changes that are associated with transitioning to a low energy demand world, and can be consistently applied to different sectors.

In this literature review exercise six sectors are analysed: Buildings, Transport, Food, Industry, Urban and Cross-sectors. Four ASI mitigation options were defined for each sector, and the default queries for literature searching were developed accordingly. The transport group for example distinguishes literature on shifting to cycling and walking as part of avoid, as well increased teleworking, the transport shift strategy focuses on shared economy and digitalisation, and the improve strategy on electrification of transport. The framework indicates the data needed, the literature search will give insight in to the data available and combined will allow to understand what are the current data gaps.

3. EDITS WP2 Meta database: connecting availability & needs

Contributing to the first aim of the EDITS data working group, since 2021 this working group has worked on developing a metadata repository which allows to communicate in a consistent and transparent manner about available data. A repository has been created which was shared through Github: https://github.com/iiasa/edits-data. The details of the meta database structure can be found in the WP2 deliverable of last year. The next step was to develop a user-friendly platform based on the initial repository structure. In order to do so a new website has been developed, that allows to collect the information about data and to share across the EDITS network, hosted by Utrecht University: https://edits-project.sites.uu.nl/ .

The new website is in structure very similar to the github database, however the website lowers the barrier for users to insert information about data and search through the data descriptions. The website in addition has a new function which is collecting data requests from the EDITS community as well. As such the database combines entries on data needs and data availability. Users can respond to indicated needs by replying with information about datasets that might fulfil these needs. The result is an interactive platform that allows to exchange information about data, but also by building on the EDITS community experience and knowledge could be used as a tool to identify data gaps. Therefore this activity contributes to both the first and the second aim of the EDITS data group. A more detailed description of the EDITS meta database can be found in the Appendix A.

The metadata platform has been tested with datasets used in the original github database and feedback was collected from a small group within EDITS. Feedback has been mostly positive, especially with regard to the easy accessibility and user-friendly

data submission and filtering process. Some specific suggestions have been made with regards to the explanatory text per field, linking data requests and meta data information, modifying or removing submissions and adding contact information. These suggestions have now been incorporated.

The website is ready to be shared with the EDITS data group for the next testing phase, which will be from March to April. In this phase the aim is to collect feedback from a larger group, in parallel with informing the group about how to use the platform and start to fill the database. Based on the collected feedback final adjustments to the website will be made. From May to August, we will ask the entire EDITS network to utilize the data sharing website, communicate data needs and share data on the website. The expectation is that during that period the database will be actively used. By September, before the EDITS Annual Meeting, we expect it to be a fully used database that can be presented and shared (Table 2).

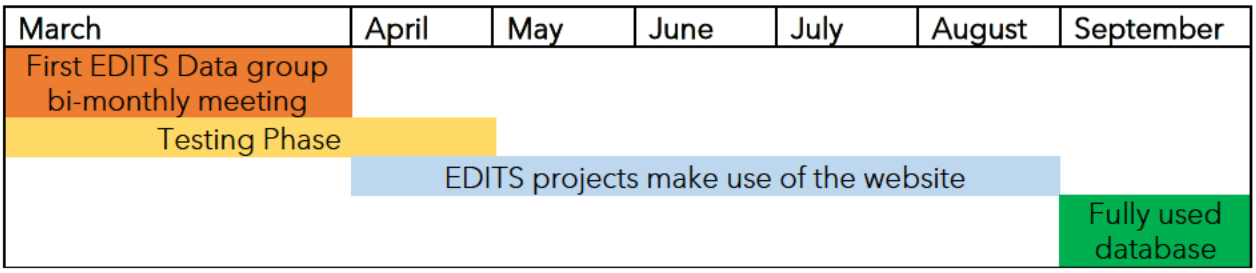


Table 2. The Timeline of the EDITS data sharing website.

Appendix A: Data sharing website structure

This appendix gives a short introduction and user guide to the EDITS metadata sharing website. It is built to enable communication about data demand and existing data by the EDITS community. It includes a welcome page, the functions of adding metadata and making data requests, searching for shared data, and viewing data requests.

The website map has been designed to be clear, user-friendly, and easy to communicate the data need through. The website landing page is the Home Page, with a short description of the EDITS website. From there you can navigate to several tabs (see also Figure 1):

- *Add Metadata*: Users can share information about demand related datasets by providing metadata that describe these dataset through the form that can be accessed through this tab. It is also possible to update the previous records or reply to data requests.

- *Search Data*: Users are able to search for the shared meta data in the EDITS community in this tab.
- *Make a Data Request*: Users can make data requests, by at least giving a short description of data desired and leaving the contact email.
- *View Data Request*: Similar to the search data tab, all the data requests can be viewed and searched here. If the user knows of data responding to a data request, they can suggest this dataset, and will be redirected to the "Add Metadata" page with a specific data request ID. This information will be published on the data request entry, so that it is clear that someone has responded to this data request.

More details on the information on the 'add metadata' and 'make a data requests' forms is presented below.

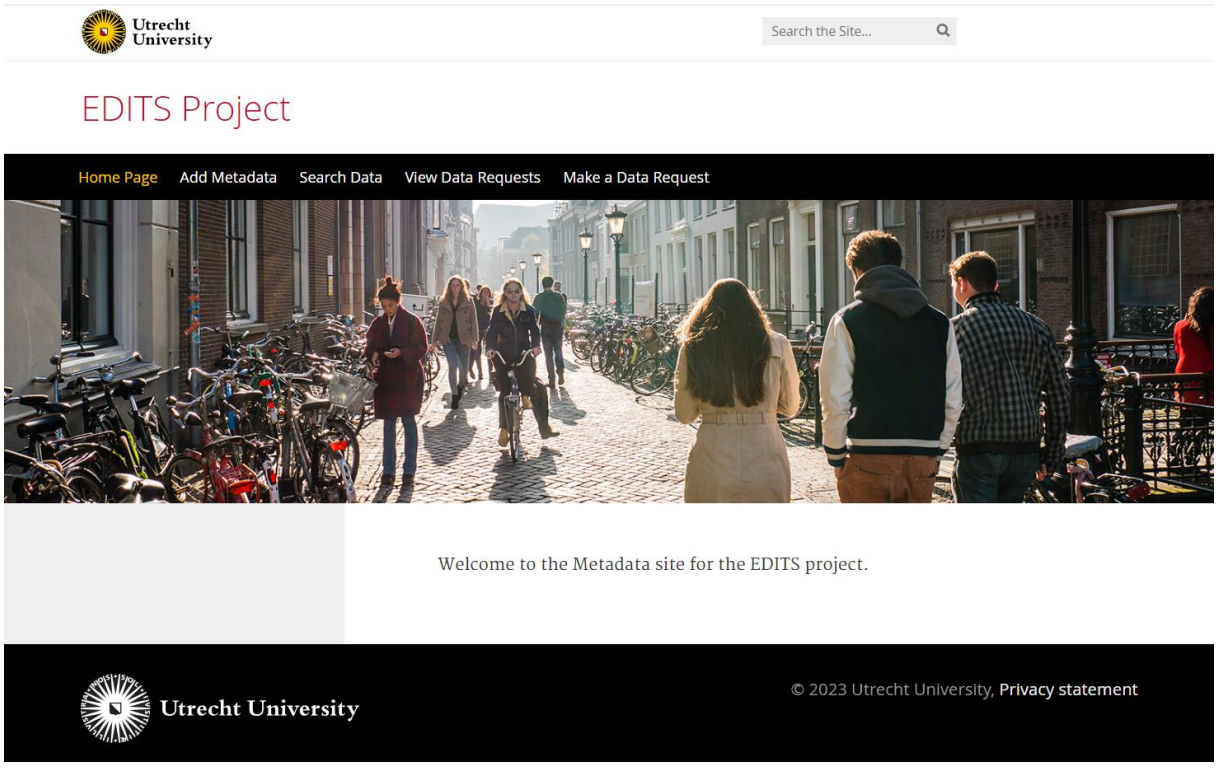


Figure 1. The entry website of the EDITS Metadata sharing platform.

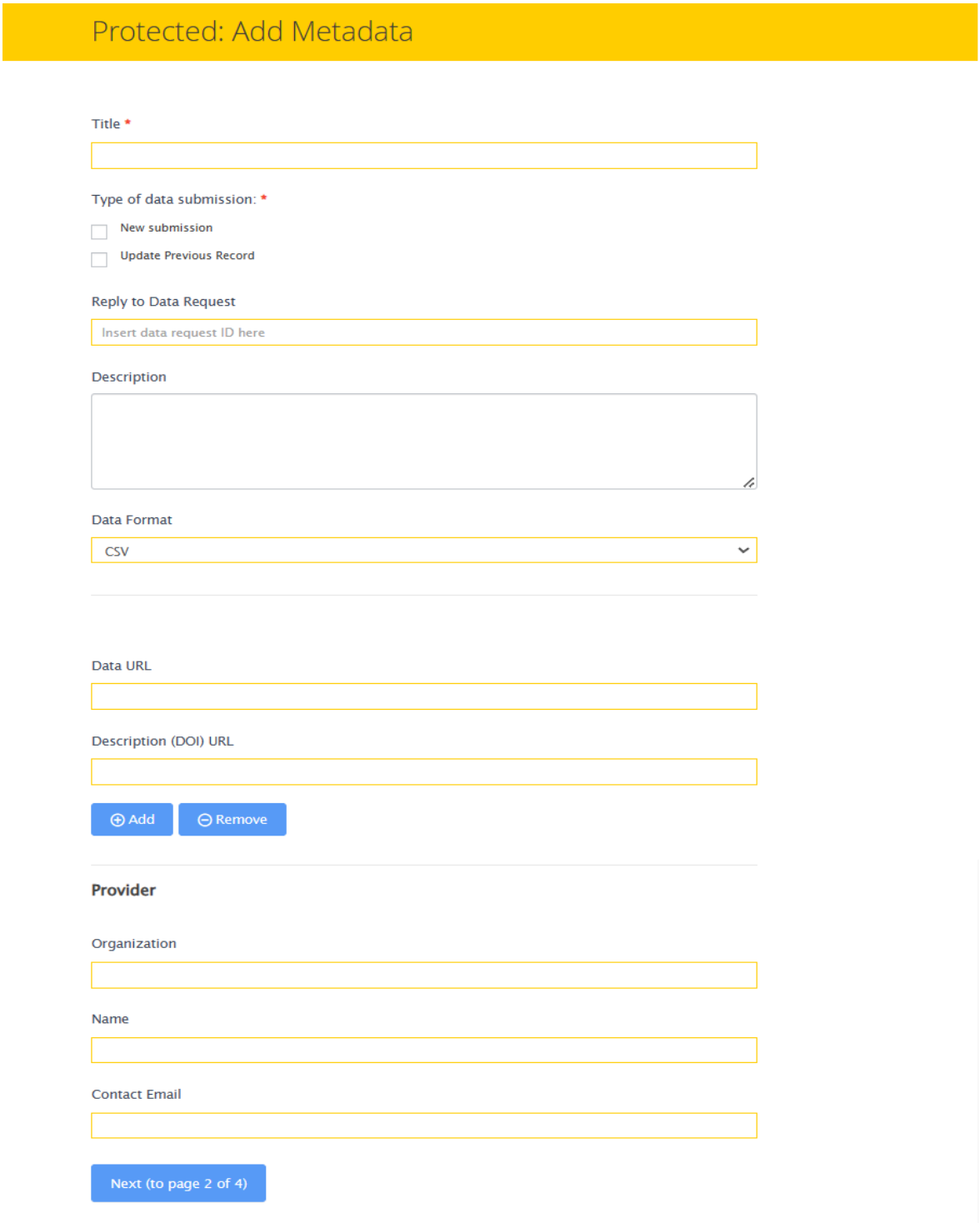
Demonstration 1. Add Metadata instructions

This section will demonstrate the steps to add metadata to the EDITS website. There are four pages containing the required information from the data provider. Currently, only the Title of Metadata, Data Submission Type, and Contact Email are required information. We will discuss future mandatory and optional information further within the EDITS dataset.

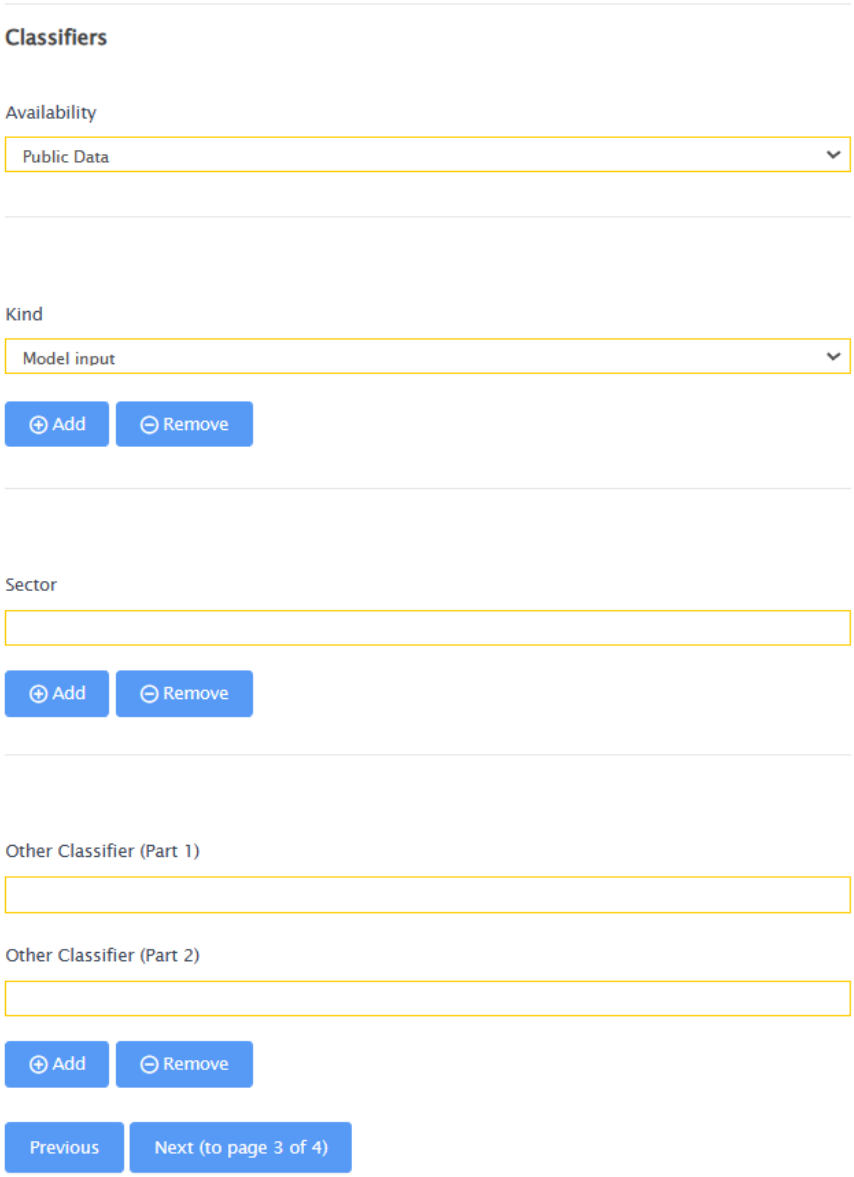
The unique design of this metadata-sharing website is that it is an interactive data supply and demand platform. Therefore, on the first page of 'Add Metadata', users can choose between submitting a new dataset, updating the previous record, or replying to a data request. In this way, data requests can be answered, and new proposals can be made in prior submissions, achieving the purpose of sharing knowledge within the energy modelling community.

The steps for adding metadata are shown below:

Step 1. **General information of metadata**. Add metadata title, define the submission type (is it a reply to a data request), and give the data format (CSV or other types of files), URL, and data provider information.



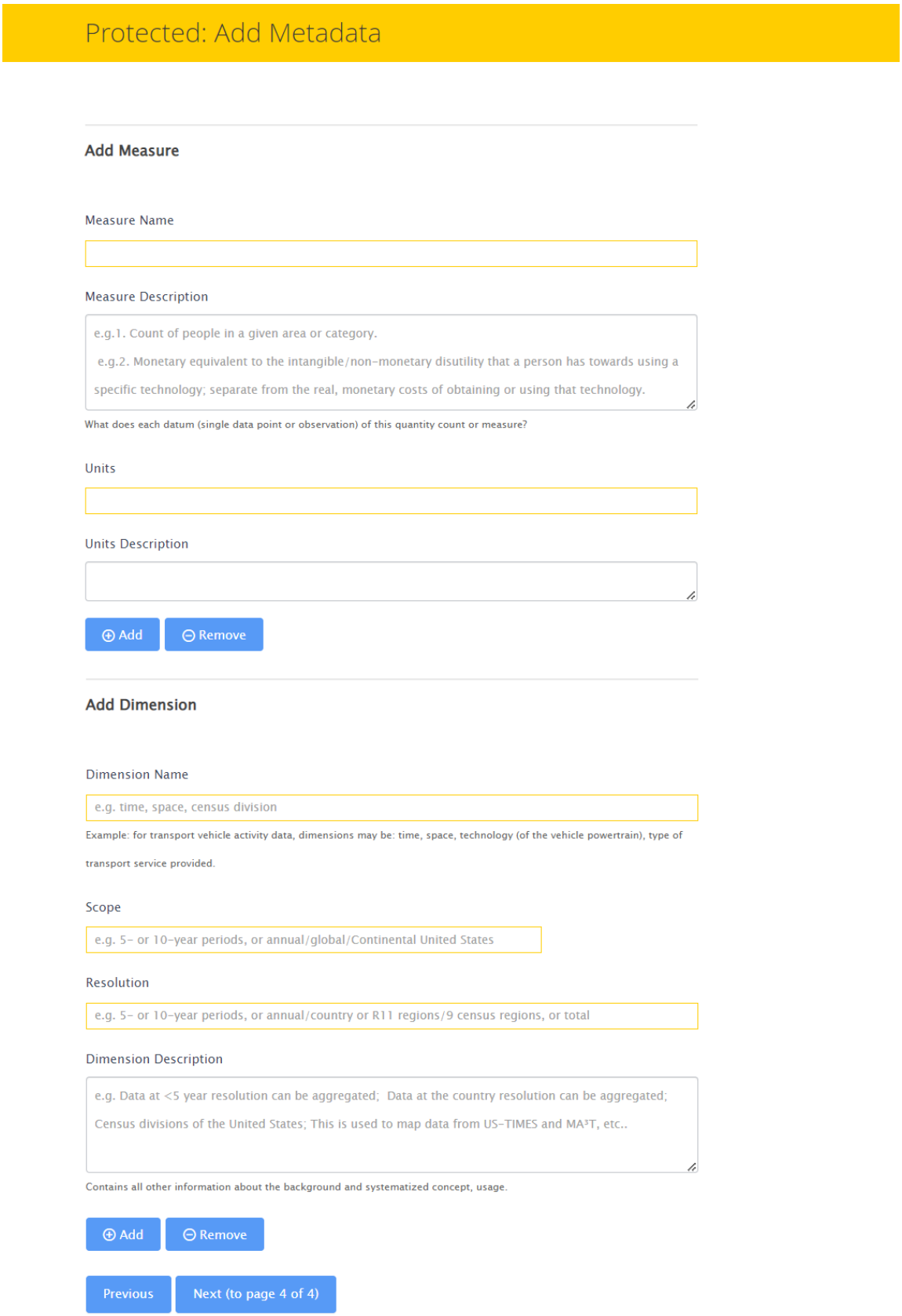
Step 2. **Classifiers of metadata.** We ask the users to provide three default classifiers: Availability (public/ registration required/ collaborators only, etc.), Kind (model input/output/core, statistic data or other), and Sector (industry/transport/buildings etc., fill in by users).



Step 3. **Measure(s) and Dimension(s) of metadata.** We ask the users to provide the main measure of the metadata, for example, population, travel distance by cars, or other types of measures. Each measure follows by its units and units' description.

Next, add the dimension(s) for the metadata. This includes dimension name, scope, resolution, and dimension description.

Users can add more measures or dimensions by the 'Add' bottom.



Step 4. **Provide your information.** We ask the users to provide at least their email address, for the future data update.

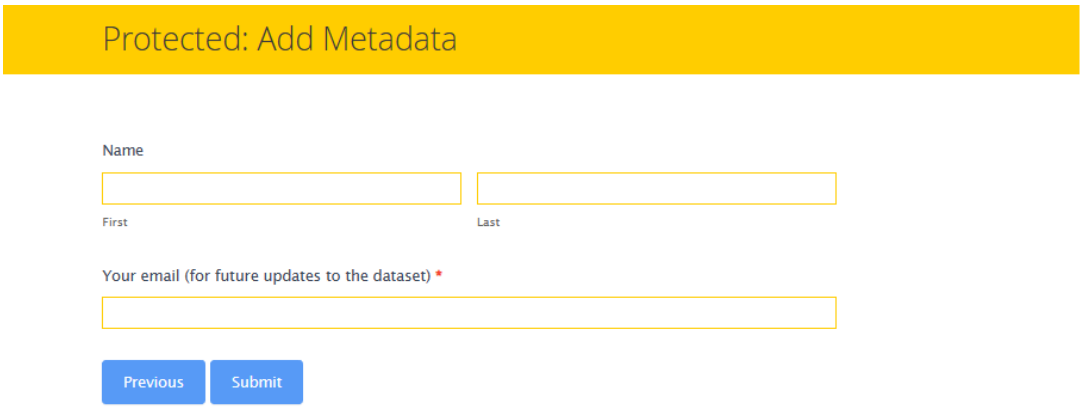


Figure 2-5. The EDITS website demonstration for Add Metadata.

Demonstration 2. Make Data Request

This section demonstrates the information users need to provide when making a data request. Except for the mandatory short description of the desired data and contact email, for the data sharing purpose, users also need to provide the data type (data format and data availability), measure name(s) and unit, and data dimension(s) (including dimension name, scope, and resolution). With the information above, the EDITS community can response to the requests more precisely, meet the data need. By submitting the request, it will appear under the 'View Data Request' tab, and the EDITS members can response to the data requests.

By comparing data requests and data submissions, data gaps in low-energy demand studies can also be illustrated, and further efforts to close the gaps can be made. Figure 6 shows the EDITS webpage for making a data request.

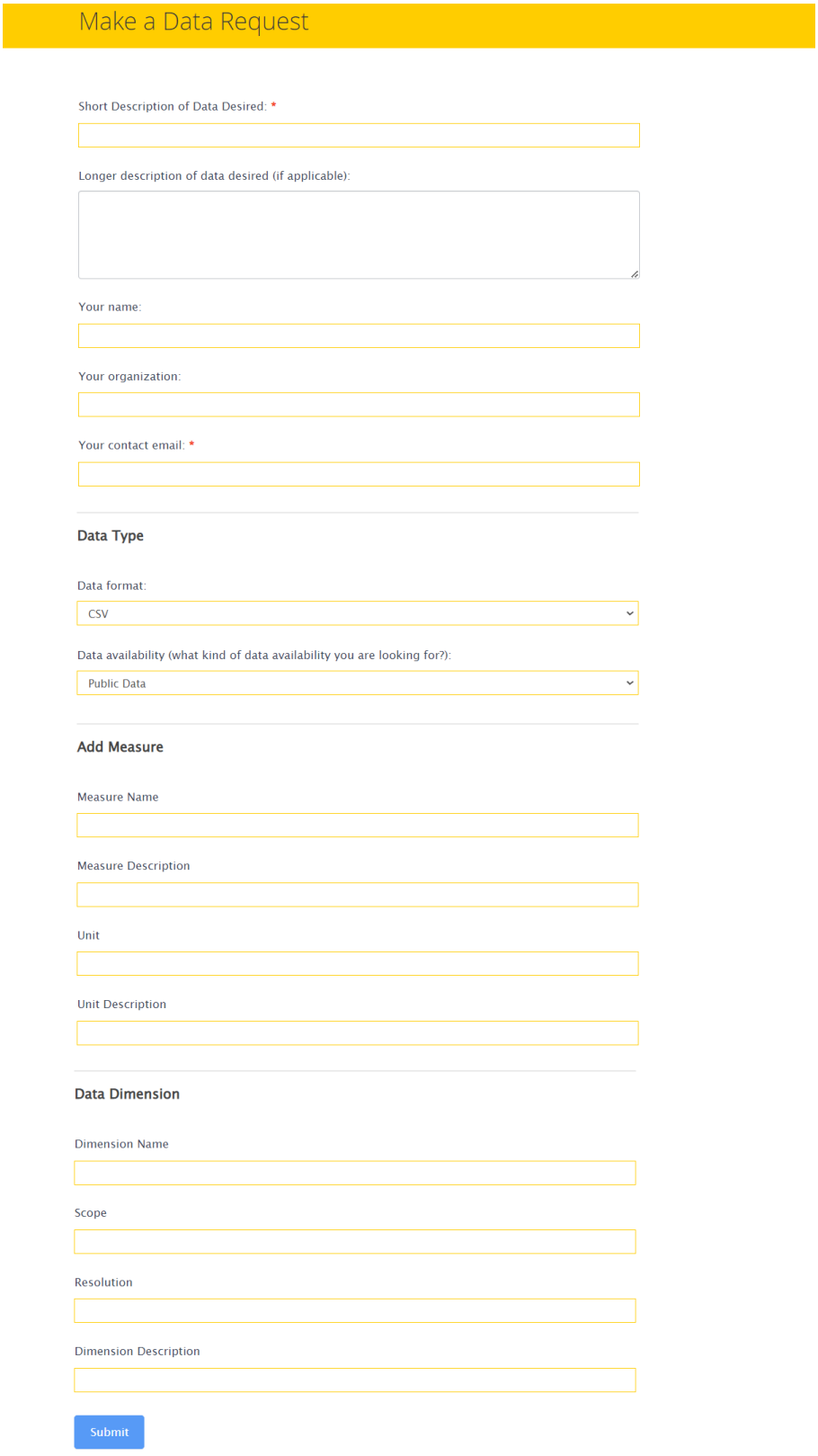


Figure 6. The EDITS webpage 'Make a Data Request'.

Is history repeating itself? Lessons from past technology transitions and false starts in the hydrogen economy

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Abstract

To decarbonize the energy system, several visions and scenarios have been proposed over time regarding the transition to a hydrogen economy. This research identifies the main proposals that have been made at different stages of history and draws lessons from the advances and failures. For this, we analyze the historical dynamics of technological substitution, comparing the formation time of emerging innovations and the decline of existing technologies. The sample of 14 transition processes includes different types of technologies (communication, consumer goods, transport, industry, energy supply), at different periods (recent and old). The results highlight the slowness of technological substitutions in transport and industry in the past. The analysis compares the role of cost and infrastructure in the transition to automobiles in the United States and to electric cars in Norway more recently. It shows that the falling cost of the new technology preceded technological substitution, which preceded the increase in gas stations and charging stations, respectively. The chapter concludes by presenting strategies based on historical experience that are most likely to accelerate the transition to new clean innovations such as hydrogen in the future.

Acceptability of climate change mitigation pathways
A pilot study

Robert Görsch & Linda Steg
With the help of Katharina Gebhard, Stina Held, Nathan McCabe, Maria Reinstrom & Rebecca Schulz

Goal of the study

The IPCC (2018) developed illustrative model pathways that would limit climate change to 1.5C. These pathways indicate that it is theoretically feasible to limit climate change to 1.5C, and that this can be achieved in different ways. The question remains whether the pathways are also socially feasible, that is, to what extent these different pathways would be socially acceptable. We aimed to conduct a pilot study to examine the social acceptability of two of the IPCC illustrative model pathways that differ in important ways: P2 and P4. P2 aims to limit climate change to a maximum of 1.6C with no overshoot, by reducing energy demand. P4 is a resource and energy intensive scenario, resulting in temporary overshoot, in which case climate goals are achieved via negative emission technologies, such as carbon capture and storage. We aim to examine the level of public support for both pathways, and examine factors and reasons influencing the level of support.

Method

The questionnaire study was part of a Psychology Bachelor students project at the University of Groningen, the Netherlands. The study was preregistered in the Open Science Framework (see https://osf.io/r3km5/?view_only=c77cf7b0351548a0b9ea70b09e72c867). Ethical approval for this study was given by the Ethical Committee Psychology (ECP) of the Faculty of Behavioural and Social Sciences at the University of Groningen. The study was conducted as an online survey in English via Qualtrics (Qualtrics, Provo, UT), from April 26th to May 20th 2022.

Sample

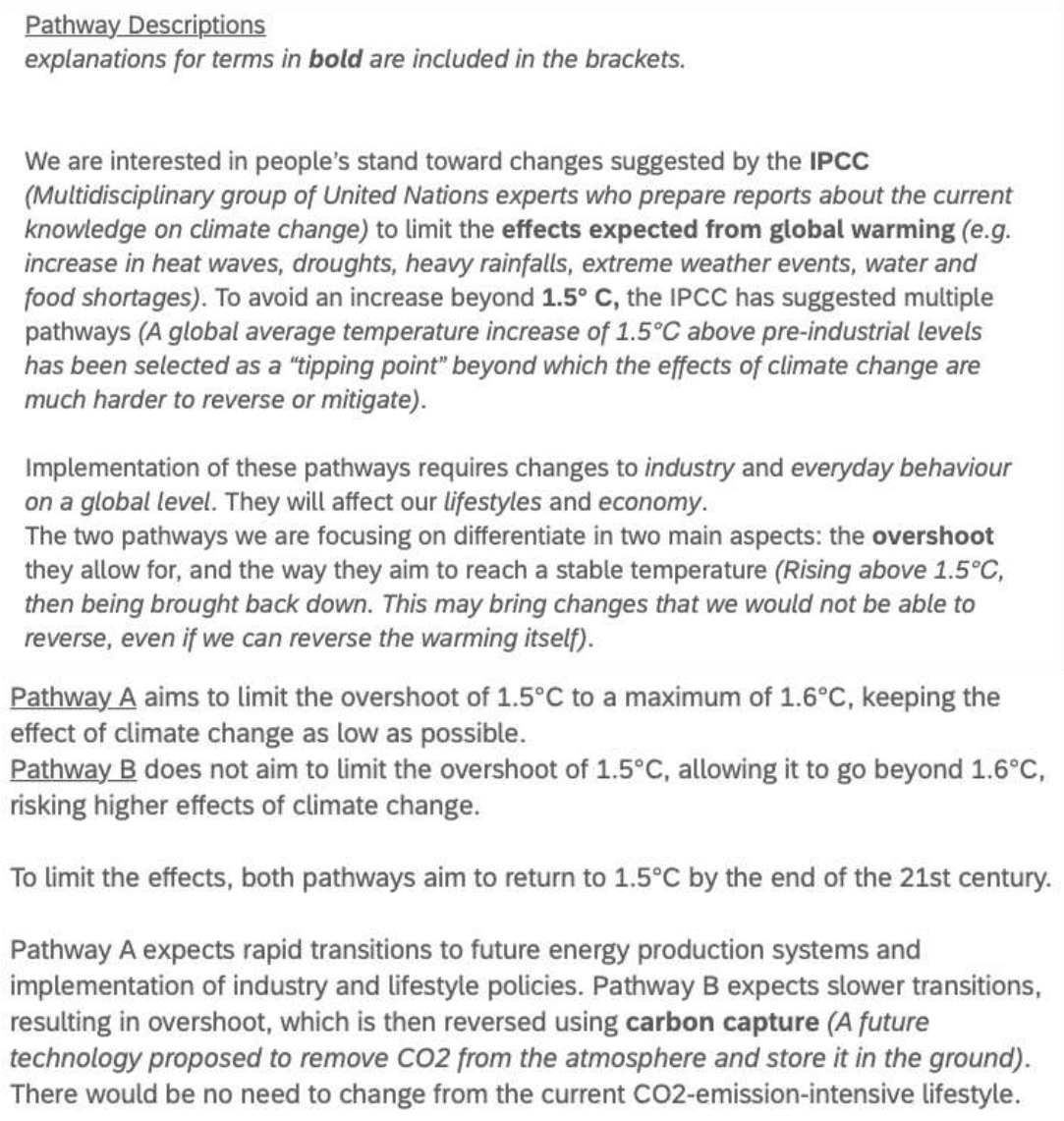
In total, 305 participants participated in the study, of which 79 (26%) were removed due to missing values. Hence, the final sample consisted of 226 (74%) participants, of which 112 (49.6%) participants were recruited via snowball sampling (e.g., via social media, asking friends and family and leaflets on notice boards), and 114 (50.4%) via the first-year psychology student participant pool of the Department of Psychology of the University of Groningen who received course credits for their participation. Participants' age ranged from 18 years to 68 years (M = 24.0, SD = 9.3); 138 (61.1%) participants identified as female, 82 (36.3%) as male, five as other (2.2%), and one (0.4%) participant preferred not to indicate this.

Procedure and Design

Before completing the questionnaire, participants were informed about the purpose and content of the study, after which they provided informed consent. Next, participants were

asked to indicate their gender, age, their perceptions of climate change risks, answered climate change knowledge questions, and were asked about personal values. After this, participants read a brief description of the two pathways, and completed four questions to test whether they accurately understood both pathways. Subsequently, they were asked how effective they find the pathways, how beneficial the pathways would be for themselves and others, and rated the distributional fairness of both pathways. Finally, participants indicated how acceptable they find the pathways, and which of the pathways they preferred. Participants also could give open ended answers about which pathway they would choose if they were policymakers, and why.
Figure 1 displays the description of the pathways participants received. IPCC Pathways P2 and P4 were labeled as Pathway A and B in the study.

Figure 1. Description of the pathways evaluated



Pathway Descriptions
*explanations for terms in **bold** are included in the brackets.*

We are interested in people's stand toward changes suggested by the **IPCC** *(Multidisciplinary group of United Nations experts who prepare reports about the current knowledge on climate change)* to limit the **effects expected from global warming** *(e.g. increase in heat waves, droughts, heavy rainfalls, extreme weather events, water and food shortages)*. To avoid an increase beyond **1.5° C,** the IPCC has suggested multiple pathways *(A global average temperature increase of 1.5°C above pre-industrial levels has been selected as a "tipping point" beyond which the effects of climate change are much harder to reverse or mitigate)*.

Implementation of these pathways requires changes to *industry* and *everyday behaviour on a global level*. They will affect our *lifestyles* and *economy*.
The two pathways we are focusing on differentiate in two main aspects: the **overshoot** they allow for, and the way they aim to reach a stable temperature *(Rising above 1.5°C, then being brought back down. This may bring changes that we would not be able to reverse, even if we can reverse the warming itself)*.

Pathway A aims to limit the overshoot of 1.5°C to a maximum of 1.6°C, keeping the effect of climate change as low as possible.
Pathway B does not aim to limit the overshoot of 1.5°C, allowing it to go beyond 1.6°C, risking higher effects of climate change.

To limit the effects, both pathways aim to return to 1.5°C by the end of the 21st century.

Pathway A expects rapid transitions to future energy production systems and implementation of industry and lifestyle policies. Pathway B expects slower transitions, resulting in overshoot, which is then reversed using **carbon capture** *(A future technology proposed to remove CO2 from the atmosphere and store it in the ground)*. There would be no need to change from the current CO2-emission-intensive lifestyle.

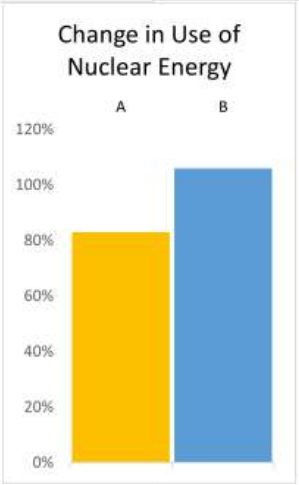
Details of the proposed energy transitions can be seen below:

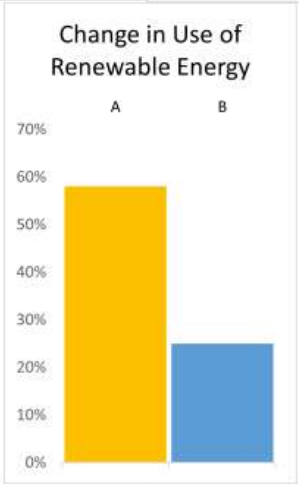
Pathway A reduces energy demand by 5% by 2030

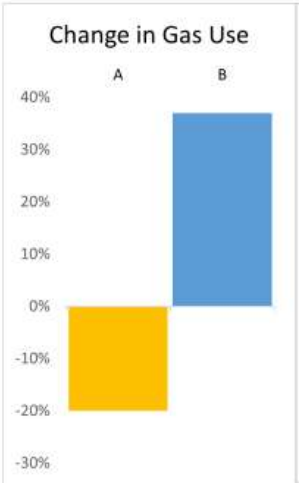
- Eating local and seasonal foods
- Reducing meat and dairy consumption
- Reducing waste in water, food and transportation industries
- Using resources more efficiently (insulation etc.)
- **Low emission innovations** *(Electric vehicles, heat pumps, district heating and cooling, future cars give off less emissions)*
- Energy-saving behaviour (walking, cycling, mass transit, lower heating)
- Organisational change (replacing business travel by video calls)
- Flood protective behaviour Heat protective behaviour (green roofs)
- Efficient water use (rationing)

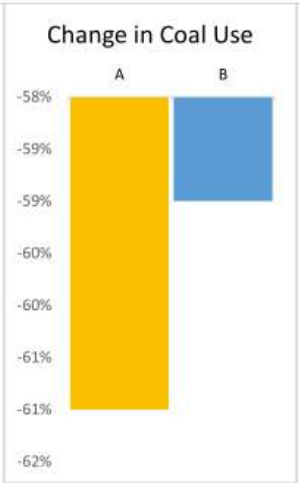
Pathway B increases energy demand by 39% by 2030

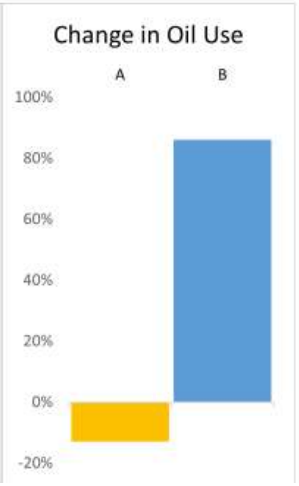
- Increased economic growth and globalisation
- Increased meat and dairy consumption
- Increased demand for fuel
- Increased worldwide shipping
- **Electrification** *(replacing technologies that use fossil fuels, e.g., coal, oil, and natural gas, with technologies that run on electricity)*
- Building desalination plants to convert seawater into freshwater











Measures

Participants indicated to what extent they find each pathway acceptable, by rating three items on a seven-point scale ranging from not at all acceptable (1) very acceptable (7), very bad (1) – very good (7), and not at all necessary (1) – very necessary (7), respectively (adapted form Perlaviciute et al., 2021). We computed mean scores on the three items. The resulting acceptability scale proved to be reliable for both pathways, Cronbach's α for P2 was 0.88, and Cronbach's α for P4 was 0.86. Participants indicated which pathway they would prefer, by choosing either pathway A or B. Participants further indicated their reasons for preferring the pathway selected.

Climate change risk perception was measured by asking participants to what extent they believe that climate change will have negative consequences for them (see Table 1). Scores could vary from strongly disagree (1) to strongly agree (7). We computed mean scores on these six items (M = 6.0, SD = .09). The internal reliability of this scale was high (Cronbach's α = 0.84).

Table 1. Items included in the climate change perception scale


To what extent do you agree with the following statements?

	Strongly disagree	Disagree	Somewhat disagree	Neutral	Somewhat agree	Agree	Strongly agree
Climate change will have negative consequences	○	○	○	○	○	○	○
The negative impact of climate change is severe	○	○	○	○	○	○	○
The thought of climate change scares me	○	○	○	○	○	○	○
Climate change can negatively affect me	○	○	○	○	○	○	○
I will experience the negative effects of climate change in my lifetime	○	○	○	○	○	○	○
I am vulnerable to the negative effects of climate change	○	○	○	○	○	○	○

Perceived effectiveness of both pathways was measured with four items: 'The pathway provides a sufficient mean to limit global warming to 1.5C by the end of the 21st century'; 'The pathway provides a clear mean for reducing the consequences of climate change'; 'The pathway facilitates limiting the effects of climate change', and 'By following this pathway, global warming would be limited to 1.5C by the end of the 21st century'. Scores could vary from strongly disagree (1) to strongly agree (7). We computed mean scores of these four items; the resulting perceived effectiveness scale was reliable for both P2 (Cronbach's α = 0.79) and P4 (Cronbach's α = 0.87).

Perceived benefits for self and others were assessed with six items, e.g., 'The implementation of pathway A[B] would positively affect my personal life [the lives of others]'. Scores varied from strongly disagree (1) to strongly agree (5). We used the mean scores of all six items. The resulting scale was reliable for both P2 (Cronbach's α = 0.87) and P4 (Cronbach's α = 0.90).

Perceived distributional fairness was measured using four items, e.g., 'Others and I will be equally affected by the implications of pathway A[B].' Scores could vary from strongly disagree (1) to strongly agree (7). We computed mean scores of these four items; the resulting perceived distributional fairness scale was internally consistent for both P2 (Cronbach's α = 0.79) and P4 (Cronbach's α = 0.84).

Results and discussion

Evaluation of the pathways

Overall, participants evaluated P2 (*M* = 5.8, *SD* = 1.1) as more acceptable than P4 (*M* = 3.3, *SD* = 1.4); *t*(225)=18.7, *p*<.001, d_z= 1.3. Moreover, in general, the majority of participants preferred P2 (N =187; 83.5%) over P4 (N=37; 16.5%). People further believe that P2 will be much more effective (*M* = 5.4, *SD* = 1.0) in limiting climate change than P4 (*M* = 3.1, *SD* = 1.3); (223)=20.4, *p*<.001, d_z= 1.4. Moreover, people perceive P2 (*M* = 3.6, *SD* = .8) as more beneficial than P4 (*M* = 2.6, *SD* = .8); *t*(224)=11.5, *p*<.001, d_z= .8 and as slightly fairer (P2 *M* = 4.3, *SD* = 1.2 vs. P4 *M* = 3.9, *SD* = 1.5); *t*(223)=2.8, *p*=.006, d_z= .19.

People generally preferred P2 over P4 for various reasons. They indicated that P2 is more effective in preventing severe negative consequences of climate change; temperature overshoot is considered dangerous by many people. For example, one participant indicated

> *"I would choose [P2] because of the threat for our earth the climat[e] change is".*

Another participant indicated:

> *"[P2], because after exceeding 1.5 degrees tipping points might make it impossible to limit the consequences of climate change".*

Related to this, P2 is believed to address the causes of climate change better than P4. For example, one participant indicated:

> *"I prefer [P2]. [P4] doesn't tackle one of the roots of climate change that is the exploitation of natural and human resources for economic growth. It doubt that constant economic growth is compatible with a sustainable handling of natural resources'.*

Furthermore, people generally prefer P2 over P4 because they have little trust in the technological solutions featuring in P4, and believe these are surrounding with a lot of uncertainty:

> *"[there] is no guarantee of effective carbon capture techniques, so it would be foolish to rely on them".*
>
> *"[P4] heavily relies on technology that's not there yet. Making policies on things that does not exist is very hard".*

On the other hand, some people think that an ambitious mitigation pathway that relies on profound behaviour change may not be supported by other citizens and may not be politically feasible. Some people further indicate that P2 may be inconvenient:

"[P4]; because [P2] won't happen, people are ignorant, can't look into the future and value short-term money and gains over securing life on this planet".

"[about P2] very difficult to convince people to change their lifestyles".

These findings suggest that most people prefer to avoid temperature overshoot, and have little trust in negative emission technologies such as carbon capture and storage. Yet, some people believe that the substantial reductions in energy demand featuring in P2 are unlikely, because of low public and political acceptance of lifestyle changes.

Relationships between acceptability, perceived effectiveness, perceived benefit, perceived fairness and perception of climate change risks

We ran two multiple regressions with perceived effectiveness, benefit, fairness and climate change risk perceptions as predictors of the acceptability of P2 and P4 respectively. Together, the four predictors explained substantial variance of acceptability of P2 (R^2 = .61) and P4 (R^2 = .57). The results were in line with our correlation analysis: P2 was evaluated as more acceptable, the more people believed P2 would be effective in limiting climate change (r = .62), the less they believed P4 would be effective in limiting climate change (r = -.26), and the more people saw climate change risks (r = .49). In addition, P2 was evaluated as more acceptable if people perceived it as having more beneficial consequences for themselves and others (r = .55) and if they believed the consequences would be distributed fairly (r = .42). Similarly, P4 is evaluated as more acceptable, the more people believe P4 is effective in limiting climate change (r = .70), beneficial for self and others (r = .62), and fair (r = .41). However, the more people see climate change risks, the less acceptable they find P4 (r = -.29). Furthermore, the more acceptable people find P2, the less acceptable they find P4 (r = -.28). The more people see climate change risks, the more they think P2 will limit climate change (r = .28), and the less they believe that P4 will limit climate change (r = -.28). We found no significant correlations between the perceived effectiveness of P2 and P4, and between the perceived effectiveness of P2 and the acceptability of P4. These findings imply that people evaluate P2 as more acceptable when they believe P2 will be more effective in limiting climate change, be beneficial for themselves and others, lead to fair outcomes, and when they see higher climate change risks. P4 is evaluated as more acceptable when people believe it will be more effective in limiting climate change risks, think it will be beneficial and fair, and when they see fewer climate change risks.

Shortcomings of the present study and suggestions for future research

The current study relied on a convenience sample of Dutch people, so the question remains whether the results can be generalized to the general Dutch population, and to other countries and cultures. Moreover, we reported correlational data, so the question remains whether acceptability judgements are predicted by perceptions of the extent to which the pathways would limit climate change and climate risks perceptions, or that the latter influence acceptability judgements, or that a third variable predicts acceptability, effectiveness and climate risks judgements. Furthermore, the question remains to what

extent the evaluations of the pathways would differ when we would have phrased the pathways differently, and when other measures and changes would be included in the pathways. Hence, future research is needed to evaluate a wider range of pathways, and to test the robustness of our findings when different phrasing and measures would be included. Moreover, future research could explore a wider range of factors that may predict the acceptability of climate mitigation pathways, such as personal values and efficacy beliefs.

In sum, our results suggest that people prefer climate mitigation pathways that imply a swift transition from fossil fuels to renewable energies and significant lifestyle changes (i.e., P2) over pathways that strongly imply a temporary temperature overshoot and that rely on negative emission technologies such as carbon capture and storage (i.e., P4). P2 is particularly among those who see more climate change risks. Acceptability of both P2 and P4 is higher the more people believe the relevant pathway will achieve climate goals. This implies that P2 is socially more feasible than P4. These results are in line with a previous study, that indicated that P2 was also evaluated as being more feasible overall (Brutschin et al., 2021).

References

Brutschin, E., Pianta, S., Tavoni, M., Riahi, K., Bosetti, V., Marangoni, G., & Van Ruijven, B.J. (2021). A multidimensional feasibility evaluation of low-carbon scenarios. *Environmental Research Letters, 15*, 064069, doi: 10.1088/1748-9326/abf0ce.

IPCC, 2018: *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* [Masson- Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

Perlaviciute, G., Görsch, R., Timmerman, M., Steg, L., & Vrieling, L. (2021). Values in the backyard: the relationship between people's values and their evaluations of a real, nearby energy project. *Environmental Research Communications*, *3*(10), 105004, doi: 10.1088/2515-7620/ac25d0.

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EDITS
Energy Demand changes Induced by Technological and Social innovations

Annual Report

Energy Demand changes Induced by Technological and Social innovations (EDITS)

February 2023

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Research Institute of Innovative Technology for the Earth, Japan

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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. EXECUTIVE SUMMARY

The **Energy Demand changes Induced by Technological and Social innovations (EDITS) initiative** started to operate at the end of 2020 after the inaugural Virtual Dialogue on Energy Demand changes Induced by Technological and Social Innovations was held in December 2020.

This report provides a review of the **third year of the initiative** and includes an overview of EDITS set-up, working methods and research community building (Part 2), activities and results of the EDITS network between March 2022 to February 2023 (Part 3), engagement and outreach during the period (Part 4), with an outlook to future directions (Part 5).

ABOUT EDITS

The **Energy Demand changes Induced by Technological and Social innovations (EDITS) initiative** brings together experts of wide-ranging disciplines to regularly discuss and deliver collaborative research regarding the multi-faceted energy demand transformation.

EDITS is a unique project that builds on bottom-up definition and formulation of research, collaborative identification of activities, remains largely informal without much of the traditional project restraints. It connects members with similar interests, capitalizes on on-going activities, while adding value through exchange of knowledge, developing methodologies together, comparing and connecting modeling, scenarios, and analytical science. EDITS explores modeling innovations across demand-side models, extends scientific knowledge on demand-side-based transformation, as well as reaches out to policy and the general public to enhance the knowledge and appreciation of demand-side measures and solutions.

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.

Specifically, EDITS aims at:

- **scoping existing work and already available demand-side models and to moving beyond** to find strength, complementarities, as well as gaps and potential development opportunities in environmental and climate policy analysis, methods and tools.
- **building a research community** with a focus on end-use, demand-side perspectives that furthers dialogue and cross-fertilization of research and policy analysis through the sharing of novel data, novel concepts, methodologies and policy analyses.
- **identifying interest and range of a future model intercomparison exercise** to **better inform policy** via structured model experiments and simulations that assess potential impacts, barriers, as well as synergies and tradeoffs 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.

SCIENTIFIC CONTRIBUTION

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]). 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 massive energy supply extensions and/or negative emissions technologies (IPCC 2018[2]). On the contrary, LED **relies on shrinking the energy system through major**

[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] IPCC 2018. Global Warming of 1.5°C Special Report. URL: https://www.ipcc.ch/sr15/

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**.

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 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. EDITS expands the scientific understanding of LED-type scenarios with a multidisciplinary angle, and explores 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.

In 2022-23, the key scientific progress[3] made by the EDITS community was:

- The **'High-with-Low' global narrative** was developed that extends and even revises the LED scenario. It is linked with the **DETRAS model**, and serves as the basis for other scientific work in EDITS.
- The EDITS Model Complementarity Protocol completed a complementarity **test phase**.
- The Model **Complementarity Protocol** has been prepared, along with the establishment of the **EDITS scenario explorer**, and a **list of participating models**.
- As part of the EDITS synthesis work, the **multi-dimensional welfare and feasibility framework** is under development.
- A **meta-database of demand-side data** has been set-up and is being filled by EDITS members.
- Sector-specific stock-taking of **model capabilities to represent High with Low scenarios for buildings, transport, and industry** has progressed into several literature review papers.
- EDITS has moved further towards **cross-sectoral research innovation**, such as exploring cross-cutting topics (urban modeling, behavioral factors of energy demand, decent living standards modeling) mostly through dedicated sessions at meetings and/or establishing new research themes.

In 2022-23, the number of publications, presentations and public outreach programs has increased[4]:

During the period, the Community has published 12 papers or book chapters with direct acknowledgement of EDITS. A further three papers have been submitted and are under review, and four more were in draft status waiting for journal responses.

COORDINATION AND COMMUNITY BUILDING

EDITS is **coordinated by the International Institute for Applied Systems Analysis (IIASA), in cooperation with Research Institute of Innovative Technology for the Earth (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.

The community is driven by shared interest, bottom-up initiation of ideas, and complementary motivations. EDITS members and teams are all involved in demand research in 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.

[3] Please refer to Part 3 of this report for more information and links.
[4] The list of papers and other publications can be found in Part 3.

The organization of the network has a flexible structure. Members are all part of the **EDITS Plenary**. The Plenary can view and comment on research, modeling, and other activities. They are all invited to regular meetings. IIASA and RITE keeps regular contact with the whole community.

Intellectual and inspirational exchanges are organized in **Quarterly Meetings and an Annual Workshop**[5]. In 2022-23, two Quarterly meetings were organized and one Annual Workshop. The Quarterlies are working meetings, focused on reporting and common discussion on the work being undertaken by members of groups, while the Annual Workshop is a combination of working meetings and inspirational discussions and explorative dialogues. The **2022 Annual Meeting took place in Laxenburg, Austria between 30 August and 1 September** with side-events on 29 August[6].

Beyond the Consortium meetings, the EDITS network organized more and more **specific meetings** in 2022-23, along specific topics and/or Working Groups (WG). These are aimed at research topics and paper preparations.

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. The working groups are: WG 1-Buildings, WG 1-Transport, WG 1-Industry, WG 2-Data, WG 3-Narratives, WG 3-Complementarity Protocol, and WG 3-Synthesis.

MEMBERS

As of February 2023, the EDITS network has **158 individual members** from **25 countries** (Figure 1) representing **62 Research Teams**. This is a minor growth from 149 members in the beginning of 2022, including a few earlier members leaving EDITS due e.g. to change of workplace.

EDITS membership is by invitation only.

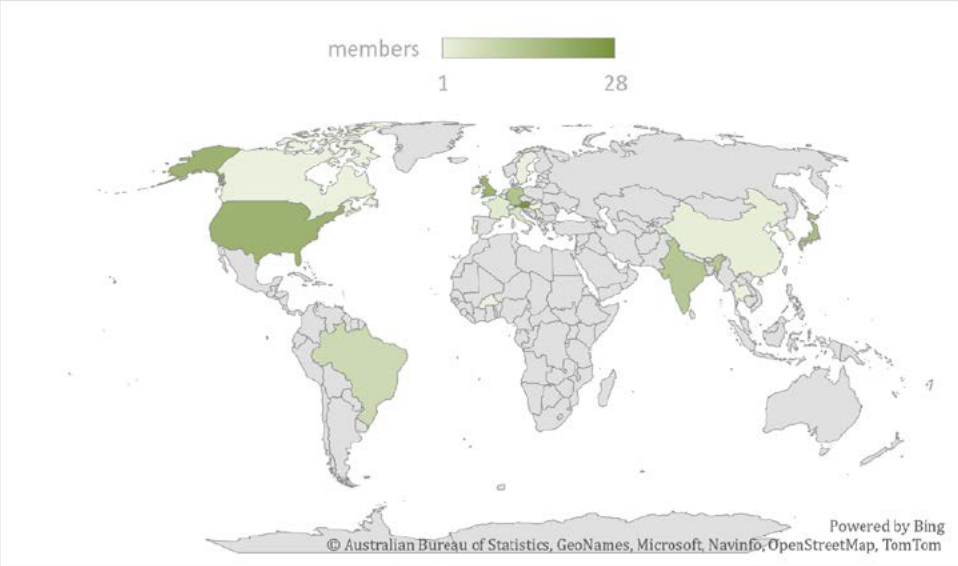


Figure 1. Geographical distribution of EDITS members

Members are free to choose their participation in the seven working groups.

[5] Part 2 of this report presents these meetings in more details
[6] A report of the Annual Meeting was prepared after the meeting and submitted to RITE.

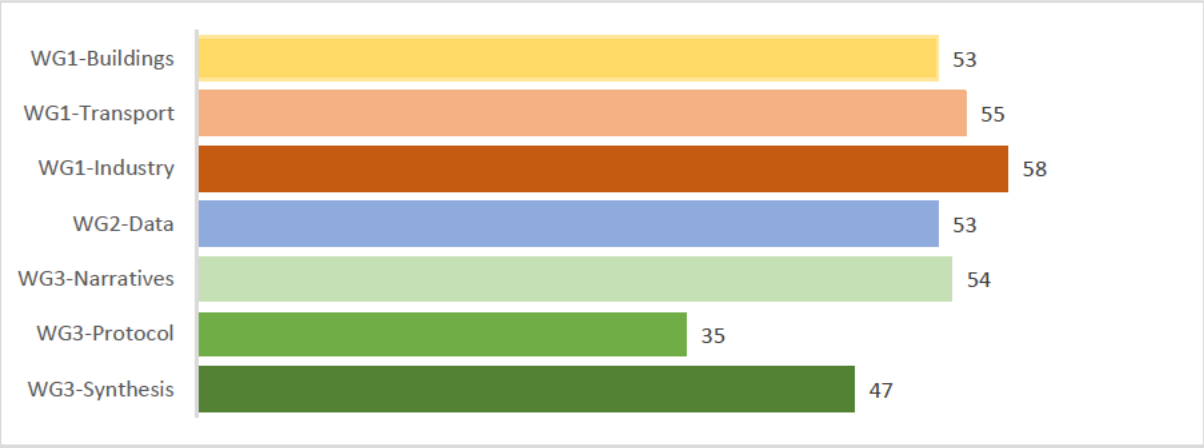


Figure 2. Working group membership as of February 2023

EDITS has been working with 29 key demand models around the world (Table 4). While 23 of these models are managed or operated by EDITS members, others have been in contact with the initiative through paper writing, surveying and other ways.

Table 1. List of demand models working with EDITS in 2022-23.

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	

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 3).

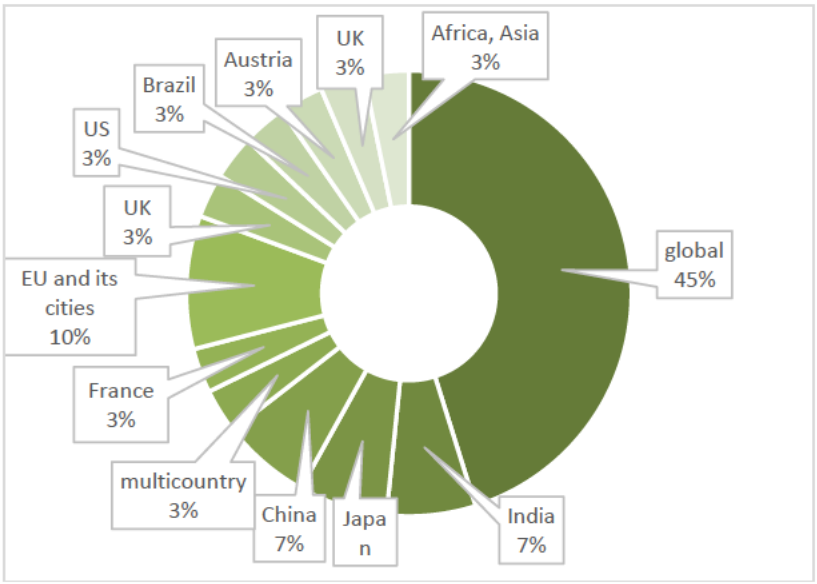


Figure 3. Coverage of the identified models within EDITS in 2022-23.

PUBLIC OUTREACH AND POLICY INTERACTION

EDITS has set-up **public channels**: a central webpage: https://iiasa.ac.at/projects/edits, a twitter account: https://twitter.com/EDITS_Community, and a Linkedin account: EDITS Network | https://www.linkedin.com/groups/14104139/

EDITS has focused on public and policy engagement in a number of ways in the period 2022-23:

- EDITS held **two EDITS webinars**:
  - **Webinar #1:** Nuno Bento | Promoting better lives is good for climate: potential co-benefits of digital convergence and sharing in consumer goodsRecording is available at https://www.youtube.com/watch?v=NjpU9zw04ak
    Time: Tuesday, 5 July 2022, 12:00 pm CEST
  - **Webinar #2:** Stefan Pauliuk | Reductions in material production induced by demand-side strategies: Implications for sustainable development
    Time: Wednesday, 15 September 2022, 12.00 pm CEST
- EDITS organized a **science-art cooperation** in the form of the EDITS-ARTS competition to create arts depiction of "life in 2050 with much less energy", in other words of the High with Low scenario[7]. The winner of the first prize was **Futuregram2050**, who created a powerful 2-minute video to portray a positive transformative future and has clearly adhered to the three evaluation criteria. The production has a compelling narrative that presents a balance between having access to modern technologies and services using modern digital solutions, while at the same time being also willing to limit the demand. Using an Instagram-like future magical ball, they tell us the story of people living in 2050, with much less energy and with competitions to lower individuals' impact on the environment using digital and circular solutions. The video can be watched at https://www.youtube.com/watch?v=OkzkY4SZeTo.

- EDITS organized **two side-events at the COP27**
  - An official side-event of the UNFCCC COP27 on 10 November 2022 "High services with low energy and resource demand for low-carbon pathways and the SDGs"[8].

[7] More can be found about the competition in Part 4 or at the website of the call (https://iiasa.ac.at/events/mar-2022/call-for-artistic-imagination-life-in-2050-with-much-less-energy) and the announcement of the winners (https://iiasa.ac.at/news/jan-2023/winners-of-edits-arts-2022-competition-life-in-2050-with-much-less-energy)

[8] More information in Part 4 and at https://iiasa.ac.at/events/nov-2022/edits-at-unfccc-cop27-high-services-with-low-energy-and-resource-demand-for-low

- An event in the Japan Pavilion on 17 November 2022 "High wellbeing with low energy demand towards a modern net-zero society"[9].

- EDITS developed **other scientific side-events and seminars** as part of larger conferences.

[9] More information in Part 4 and at https://iiasa.ac.at/events/nov-2022/rite-iiasa-side-event-on-edits-at-unfccc-cop27

PART 2. CAPACITY BUILDING AND NETWORKING

CONSORTIUM SET-UP 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, as well as modeling these. EDITS members and teams are all involved in demand research in 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. This set-up makes **EDITS informal, bottom-up and relatively self-governing with management through support**.

EDITS is **coordinated by the International Institute for Applied Systems Analysis (IIASA), in cooperation with Research Institute of Innovative Technology for the Earth (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.

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 **EDITS 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 2022-23, **two Quarterly meetings (19-20 May and 6-7 December 2022)** were organized and one **Annual Workshop (30 August-1 September 2022)**. 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 members of groups, while the Annual Workshop is a combination of working meetings and inspirational discussions and explorative dialogues.

Beyond the Consortium meetings, the EDITS network organized more and more specific meetings, along specific topics and/or Working Groups.

- **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. 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 2.

More information on the actual activities of the Working Groups in 2022-23 is found in Part 3.

Table 2. EDITS Working Groups in 2022-23

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

EDITS MEMBERSHIP AND COLLABORATION

As of February 2023, the EDITS network has **158 individual members** from **25 countries** (Figure 1) representing **62 Research Teams**. This is a minor growth from 149 members in the beginning of 2022, including a few earlier members leaving EDITS due e.g. to change of workplace.

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).

EDITS members are offered to choose Working Group membership. **74% of all members take part in at least one Working Group (as growth from 63% in 2021)**, which indicates a higher level commitment than being "only" a plenary member (but not always). Figure 2 illustrates the membership status of each Working Group. Gender (Figure 4) and geographical distributions are not fully balanced yet, but there are efforts to improve this situation in the coming years.

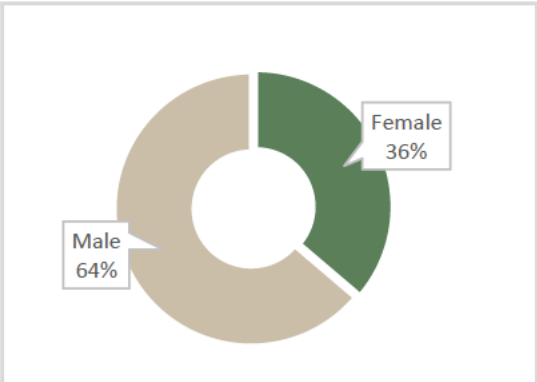


Figure 4. Gender distribution of EDITS members (individuals) as of February 2023.

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.

EDITS have collectively identified **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 3. List of demand models in the sight of EDITS in 2022-23.

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	

The host organizations of the models identified in EDITS are scattered around the globe (Figure 6).

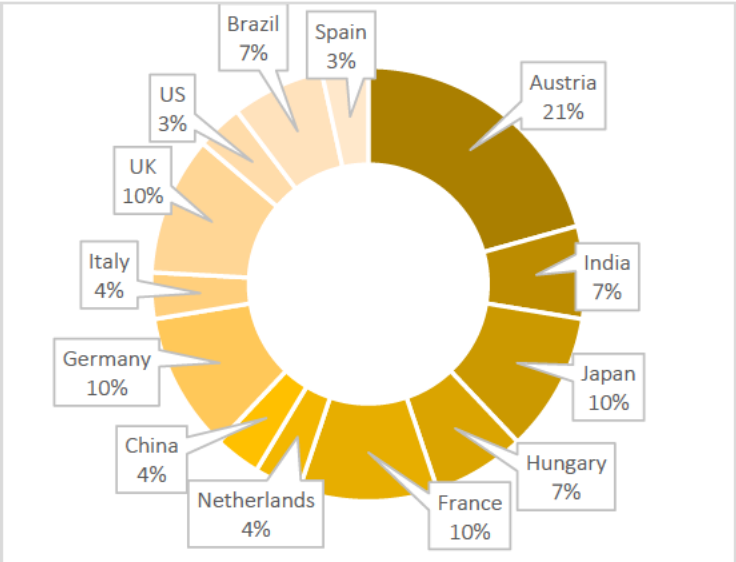


Figure 5. Host countries of the identified models within EDITS in 2022-23.

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.

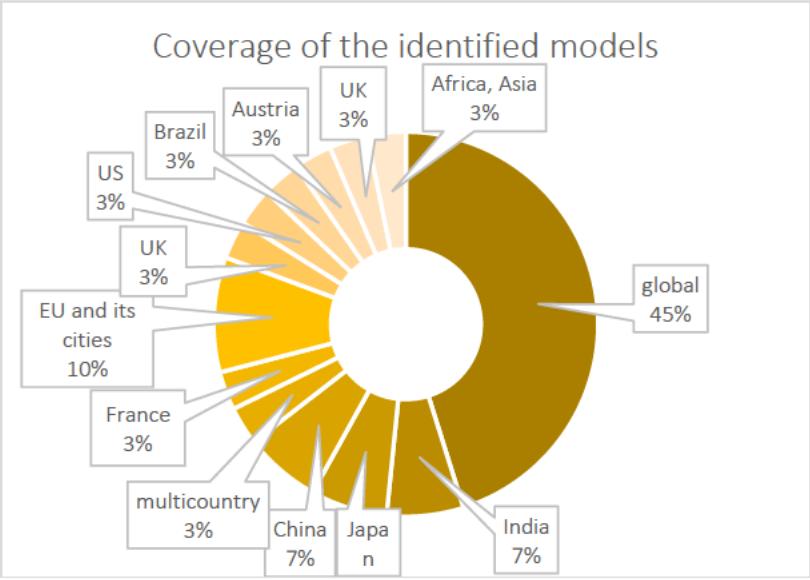


Figure 6. Coverage of the identified models within EDITS in 2022-23.

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.

A tailored style was developed and used in all materials in 2021, which remained in use until now.

- 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 8). 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.

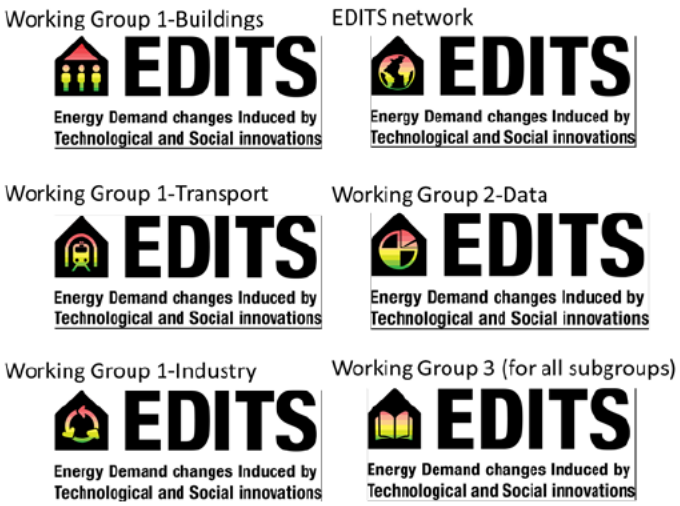


Figure 7. EDITS and Working Group logos.

REGULAR MEETINGS

In 2022-23, **two Quarterly meetings** were organized always online (zoom):

Quarterly 2022/1, Session 1 was held on 19 May (49 participants). The meeting was an opportunity for all WGs to give an update and call for input for the work plans in 2022-23. The topics of the upcoming Annual meeting were also discussed and decided.

Quarterly 2022/1, Session 2 was held on 20 May (34 participants). This meeting was used as the showing of the EDITS-ARTS applicants to the whole Consortium. The EDITS Evaluation Committee had a chance to meet the applicants in person, who were all asked to present their art in 5 minutes. Out of the 23 eligible submissions, 16 shortlisted arts were pre-selected and viewed on this occasion. The types of arts in the short-list are shown in Figure 9

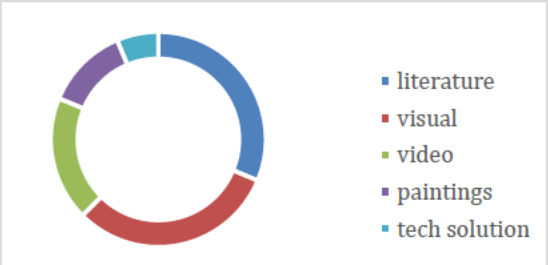


Figure 8. Types of arts short-listed in the Competition.

Quarterly 2022/1, Session 1 was held on 6 December (79 participants). This session provided an overview of what has been done in 2022 by each Working Group, what the key outputs are and how the WGs planned to move forward. Potential new streams in 2023 were proposed, for example a new WG on well-being and the determinants of low energy-high quality life. A key focus of the meeting was to progress with the concerted efforts in terms of developing and populating the EDITS energy-demand modeling protocol.

Quarterly 2022/1, Session 2 was held on 6 December (64 participants). This session presented the idea of fast-track streams. A Call for proposals was announced at the Annual, with further details sent out in November 2022 to solicit ideas for specific, small-team collaborations aiming at brisk outputs. The teams with proposals in mind had an opportunity to present, get feedback and attract interest and comments.

WORKING GROUP MEETINGS AND DEDICATED MEETINGS

Actual work in the WGs was shifted to periods between the Regular Meetings, and these are presented in Part 3 under Working Group activity review.

EDITS ANNUAL MEETING 2022

The EDITS 2022 Annual Meeting took place between **30 August and 2 September in Laxenburg, Austria** as an **in-person meeting** with more than half of the EDITS members. There was a possibility to join online in special circumstances. Online connection was provided through zoom-links without hybrid set-up, to allow participation of people with mainly last minute cancellations for personal (e.g. COVID) reasons.

The plenary and breakout sessions provided a platform for **dialogues on provocative topics**, including (1) what is needed to make the global LED narrative relevant in the diverse subglobal context, (2) how to successfully present and communicate about LED scenarios, (3) what are the benefits of going towards LED futures.

Each **working group had dedicated sessions** to proceed with their on-going or upcoming work, and they used their sessions as appropriate for their working stages. The Working Groups completed test phases and preparations during 2021-22, which were presented at the Annual Meeting in the break-out groups. Building on these, the Annual Meeting served as a platform to identify next work streams to pursue to progress towards further research outputs.

Finally, **special sessions to showcase research relevant to EDITS and energy demand by individuals and teams** were also organized. Session 5 invited ideas that could lead to small internal groups to work on selected dedicated topics, while Session 6 provided space for research that EDITS members carry out either as part or outside of EDITS, but that they thought would be interesting for the Community.

Annual meetings in 2019, 2020 and 2021 covered the following themes:

- Service demands: conceptual and theoretical foundations;

- Policy relevance and systems perspective;
- Modeling the end-use sectors: industry sector, buildings sector, transport sector;
- Parameters, variables, model outputs;
- Endogeneity and interlinkage opportunities;
- Data challenges and datagaps;
- Discussion of future directions, decisions and next steps.

The slides of the presentations, the recordings of the sessions, photos from the meeting are available at the EDITS sharepoint, which EDITS members have direct access to. Access is limited to EDITS members or can be granted on a case by case basis (e.g. to METI).

A full summary of the Meeting was submitted to RITE in September 2022, and can be also found in Annex 1.

PART 3. RESEARCH AND MODELING

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.

RESEARCH HIGHLIGHTS

The EDITS Community has worked in a broad range of themes and a variety of methodologies under the different Working Groups. An overview of key research highlights is presented below, and expanded in the Working Group section.

1) The **'High-with-Low' global narrative** was developed that extends and even revises the LED scenario. It is linked with the **DETRAS model**, and serves as the basis for other scientific work in EDITS.

Three central themes of decent living standards for all, innovation and granularity, and digitalisation, inter-link to generate synergistic benefits for inclusive wellbeing, adaptability to local contexts, accelerated diffusion, and shared infrastructures. These synergies are not deterministic; they depend on specific governance institutions and other mechanisms for coordinating a highly distributed global transition. Although the aim of this report is to develop and enrich narrative aspects, building on earlier work from the global low energy demand (LED) scenario, the final section sets out some guidelines and parameterisations for quantitative model interpretations of the High-with-Low scenario. As sectoral and systems-level models at global, regional and national scales vary widely in their structure and function, these guidelines are not universally prescriptive but rather define a set of quantitative reference points against which model inputs, processes, and outputs can be iteratively tested for consistency.

2) The EDITS Model Complementarity Exercise has completed a **test phase,** developed the **Model Complementarity Protocol**, which was commented and evaluated by model teams, along with the establishment of the **EDITS scenario explorer**, and a **list of participating models**.

Each modeling team should run the following four scenarios:

	W/o climate policy	W/ climate policy
Default demand-side solutions	**DefDem_noPol**	**DefDem_15**
HwL (low energy & material demand & granular technology improvement, etc.)	**HwL_noPol**	**HwL_15**

EDITS will distinguish two tiers of scenarios. Tier 1 is obligatory for every modeling team participating in the exercise whereas Tier 2 is an optional (but valuable) addition.

Tier 1

- DefDem_noPol: Model default without climate policy, preferably SSP2 socioeconomics.

- HwL_15: full/partial implementation of HwL narrative and DETRAS quantification. Includes 1.5-consistent climate policy (you use your “default” 1.5C climate policy if you have one). Some deviations from the LED study are acceptable but should be documented.

Tier 2

- DefDem_15: DefDem_noPol with climate policy that is consistent with a warming target of 1.5K.
- HwL_noPol: HwL_15 without climate policy.

3) As part of the EDITS synthesis work, the **multi-dimensional welfare and feasibility framework** is under development.

Brutschin et al. have introduced a framework that enables a multidimensional comparison and evaluation of scenarios from a wellbeing perspective. To assess the usefulness of the framework, they compare a few illustrative scenarios using key proposed indicators. While this analysis is purely illustrative, several significant insights are gained. Firstly, it is essential that the current generation of scenarios report on more variables, especially those relating to the provision of services. For example, in the building sector, only the SDP scenario reports the assumed floor space.
As the concept of wellbeing is multidimensional with no substitution between dimensions, there are significant trade-offs along key dimensions. The SDP scenario assumes a substantial reduction in food demand in developed regions, with a later reduction in developing regions, freeing up space for continued rising consumption patterns in other sectors. Yet it is not clear whether such a fast shift in dietary patterns will be feasible.

4) A **meta-database of demand-side data** has been set-up and is under development.

A metadatabase was already created in 2021. Some inserts were collected as test, but a broader up-take was not obrseved. Therefore, it was agreed in the WG-Data that there is still need for the meta database, but in a more user-friendly format. A site was created where members (with restricted access) can submit dataset information and/or request datasets from colleagues (Figure 10).

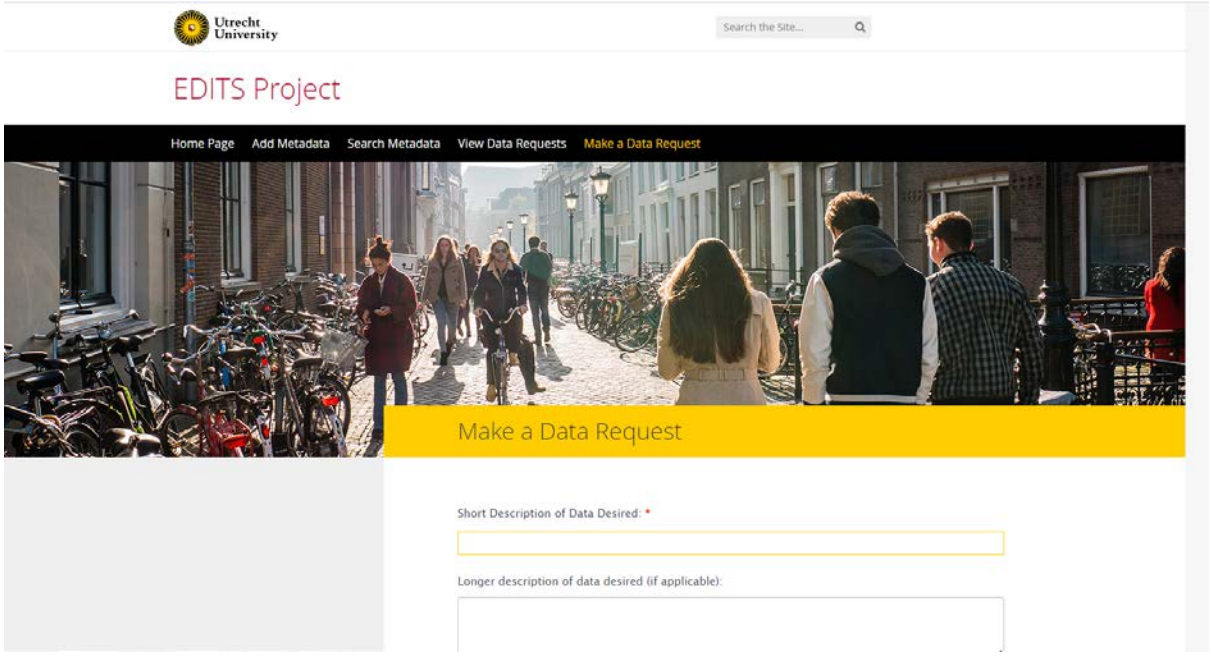


Figure 9. Metadatabase

5) Sector-specific **model mapping for buildings, transport, and industry** has progressed into a number of review papers.

Three sectoral papers have been under preparation since 2021. Each of these are in a different stage, but are well progressing. They will assess the possibility of modeling LED factors (bahvaioural, technological, infrastructural changes and megatrends) in demand-models. The draft papers for buildings and industry will be published in ARER. The review paper for transport is yet to be decided.

6) EDITS has moved further towards **cross-sectoral research innovation**, such as exploring cross-cutting topics (urban modeling, behavioral factors of energy demand, decent living standards modeling) mostly through dedicated sessions at meetings and/or establishing new research themes.

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 Part 1. Here, a report on their 2022-23 activity is presented.

At the moment, the demand research in EDITS is focused on **reviews of the current practices and gaps**, as well as **selected focused topics** (e.g. energy security, sufficiency, real-life cases studies), 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 looking into **selected outcomes of scenario comparisons, e.g. on wellbeing**.

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.
- They identify critical research gaps for the understanding, conceptualization and modeling of sector or cross-sectoral topics in the coming years.

Working Group 1-Buildings

1) Aims of the subgroup in 2022-23

- Finish and submit model review paper for the LED modeling in the buildings sector.
- Identify gaps and expand knowledge in building sector modelling practices and concepts.
- Kick-off dedicated themes to build on the review paper.

2) Research and results in 2022-23

- Review paper ("Modelling low energy demand futures for buildings – Current state and research needs") is submitted and accepted with major changes, as well as resubmitted.
- 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) Activities and meetings in 2022-23

- Regular series of ca. bi-monthly working meetings focused on the paper writing;
- Active participation at the Quarterlies and the Annual Workshop;
- Discussion about new themes, and identification of work streams:
  - Behavioural and lifestyle changes
  - Circular and sharing economy

- Energy access and equity + Decent living standards
- National and international regulations and policies.

4) Activities planned for 2023-24

- The theme "Decent Living standards modeling in India" is planned as a fast-track work stream, headed by Alessio Mastrucci
- The theme "National and international regulations and policies" will be headed by Leila Niamir
- The theme "Real-life case studies of LED applications" will be headed by Benigna Boza-Kiss
- A data-gaps analysis (under WG-Data) is lead by Leila Niamir, where Buildings, Transport, Industry, Food and Urban sectors are assessed.

5) Cross-WG collaborations

- Data and information knowledge exchange, contribute to (review) papers (WG2)
- Modelling protocol, complementarity exercise, and narratives (WG3)
- Cross-sectoral collaboration, e.g. Industry review paper

Working Group 1-Transport

- Aims of the subgroup in 2022-23

- 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.

- Research and results in 2022-23

- Literature review;
- A transport modeling review paper was started: conceptual development and draft outline; Paper draft is being developed.
- Contributed to WG-Data and WG-Protocol.

- Activities and meetings in 2022-23

- Shared meetings with WG2-Data, developing data-gaps and data availability assessment for transport;
- Co-lead meetings.

- Activities planned for 2023-24

- A transport sector LED-modeling review paper is planned
- Thematic theme papers on the implementation of LED scenario under the ITF transport demand models (e.g. Freight, urban passenger and interurban passenger)
- A data-gaps analysis (under WG-Data) is lead by Leila Niamir, where Buildings, Transport, Industry, Food and Urban sectors are assessed.

Working Group 1-Industry

1) Aims of the subgroup in 2022-23

- Finalizing the Industry demand-model review paper "A review of industry modelling and demand-side transformations for low energy and materials demand futures"

2) Research and results in 2022-23

- Literature review of industry and material demand modeling in the scope of LED scenarios with coding and group effort;

- Paper precis submitted to ARER, which was accepted.
- Paper content:
    - Generalized socio-metabolic industry systems definition developed
    - 8 modelling traditions/families identified, described & summarized in 2 productive WG meetings
    - Conceptualization of „Wellbeing – Services - Materials&Energy – GHGs“ cascade developed
    - Structure for empirical review part developed

3) Activities and meetings in 2022-23

- Working meetings mostly linked to Quarterlies (organized for the same or close dates), several sit-down / writing meetings
- Collaboration meetings with WG-Data and WG-Protocol
- On-demand follow-up meetings

4) Activities planned for 2023-24

- Finish and submit the review paper.
- A data-gaps analysis (under WG-Data) is lead by Leila Niamir, where Buildings, Transport, Industry, Food and Urban sectors are assessed.
- Fast track proposal: „Material stocks requirements for achieving DLS and high wellbeing around the world“ (Wiedenhofer/Streeck et al.)
- Modelling activities by Stefan Pauliuk et al. on bottom-up estimation of selected DLS and their life-cycle & stock requirements
- Preparing MISO-2 stock-flow modelling for LEMD scenarios (Wiedenhofer et al.)
- Paper at the 11th International Conference on Industrial Ecology (ISIE2023), Leiden, Netherlands 2-5 July 2023. Lower energy and materials demand towards net-zero GHG futures for industry – a critical review of the potentials, strategies, and modelling approaches required for transformative insights

5) Cross-WG collaborations

- WG buildings review
- WG data & model complementarity/intercomparison
- WG narratives

Working Group 2: Data and models

1) Aims of the subgroup in 2022-23

- Meta database
- Data group organisation

2) Research and results in 2022-23

- 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
    - The metadata repository has been recreated for easier use: https://edits-project.sites.uu.nl/wp-activate.php
- Review paper on data needs was started and the concept and framework set-up.

3) Activities and meetings in 2022-23

- Side-event at the Annual Meeting, and a number of dedicated online meetings;

4) Activities planned for 2023-24

- Fill-up the metadatabase;
- A data-gaps analysis is lead by Leila Niamir, where Buildings, Transport, Industry, Food and Urban sectors are assessed.
- Fast track paper: Improved energy demand indicators
- Biweekly meetings to boost activities.

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 2022-23

- 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 2022-23

- A quantitative framework 'DETRAS' decomposing two-region sectoral final energy 2020-2050 in LED into Activity, Structure, and Intensity components. Available here.
- Publication of High with Low scenario narrative, which is a more granular narrative of the LED scenario, with a focus on innovation, digitalization and urbanization and well-being.

3) Activities and meetings in 2022-23

- Working meetings with sub-teams, who have produced analyses in the topics: 1) digitalization and dematerialization, 2) decent living standards, 3) innovation.

4) Activities planned for 2023-24

- Work with local teams (national modelers) to further disentangle the High with Low narrative;
- Collaborate with WG Protocol to model HwL.

Working Subgroup 3-Complementarity Protocol

1) Aims of the subgroup in 2022-23

- 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 2022-23

- Test run of the MCE = Demonstrate the proof of concept for MCE
- Full MCE was initiated. A sign-up of modeling teams was carried out.
- The MCE Protocol was developed and commented by modeling teams.
- IIASA Scenario Explorer space created: Template, model registration completed.

- The data template is available from https://bit.ly/edits-outputs. For this round only Tier 1 is collected, incl. Emissions, Carbon Price, GDP, Population, Final Energy, Energy Service Demands, Primary Energy.

3) Activities and meetings in 2022-23

- Biweekly meeting of the core group
- Working Group meetings at the Quarterlies.

4) Activities planned for 2023-24

- Work with local teams, modelers to upload data into the template and Scenario Explorer.
- Assess the submitted scenarios.
- Progress to Tier 2 level submissions.

Working Subgroup 3-Synthesis

1) Aims of the subgroup in 2022-23

- The sub-group is responsible for synthesis across scenario implementations at different sectors and levels.
- 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 2022-23

- A "Framework to Evaluate Desirability of LED Scenarios" has been co-developed by IIASA and CMCC;

3) Activities planned for 2023-24

- Regular bilateral meetings between the co-leads in order to progress with the assessment on well-being and other themes.

PUBLICATIONS AND PRESENTATIONS

During the period, the Community has published 12 papers or book chapters with direct acknowledgement of EDITS. Further 3 submitted and under review, and 4 more were in draft status waiting for journal response.

1. Souran Chatterjee, Vassilis Stavrakas, Gabriel Oreggioni, Diana Süsser, Iain Staffell, Johan Lilliestam, Gergely Molnar, Alexandros Flamos, Diana Ürge-Vorsatz. 2022. Existing tools, user needs and required model adjustments for energy demand modelling of a carbon-neutral Europe. *Energy and Social science*. https://doi.org/10.1016/j.erss.2022.102662
2. Clare Hanmer, Charlie Wilson, Oreane Edelenbosch, Detlef Van Vuuren. 2022. Translating Global Integrated Assessment Model Output into Lifestyle Change Pathways at the Country and Household Level. *Energies* 15(5). https://doi.org/10.3390/en15051650
3. Shreya Some, Joyashree Roy, Joyee Shairee Chatterjee, M. Huzaifa Butta. 2022. Low demand mitigation options for achieving Sustainable Development Goals: Role of reduced food waste and sustainable dietary choice. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2022.133432
4. Doris Virág, Dominik Wiedenhofer, André Baumgart, Sarah Matej, Fridolin Krausmann, Jihoon Min, Narasimha D. Rao, Helmut Haberl. 2022. How much infrastructure is required to support

decent mobility for all? An exploratory assessment. *Ecological Economics*. https://doi.org/10.1016/j.ecolecon.2022.107511
5. Molnár, G., Ürge-Vorsatz, D., & Chatterjee, S. 2022. Estimating the global technical potential of building-integrated solar energy production using a high-resolution geospatial model. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2022.134133
6. Sascha Nick and Philippe Thalmann. 2022. Towards True Climate Neutrality for Global Aviation: A Negative Emissions Fund for Airlines. *Journal of Risk and Financial Management*. https://doi.org/10.3390/jrfm15110505
7. Ayami Hayashi, Takashi Homma, Keigo Akimoto. 2022. The potential contribution of food wastage reductions driven by information technology on reductions of energy consumption and greenhouse gas emissions in Japan. *Environmental Challenges*. https://doi.org/10.1016/j.envc.2022.100588
8. Boza-Kiss, B., Schmatzberger, S., Fernández Álvarez, X., Broc, J-S., Ürge-Vorsatz, D.. 2022. Energy efficiency first policy landscapes for buildings: case studies in Germany, Hungary and Spain. *European Council for an Energy Efficient Economy (ECEEE)*. ID 7-168-22. link
9. Chatterjee, S., Kiss, B., Ürge-Vorsatz, D., Teske, S.. 2022. Decarbonisation Pathways for Buildings, In: Teske, S. (eds) Achieving the Paris Climate Agreement Goals. *Springer, Cham*. https://doi.org/10.1007/978-3-030-99177-7_7
10. Gregory Nemet, Jenna Greene. 2022. Innovation in low-energy demand and its implications for policy. *Oxford University Press*. https://doi.org/10.1093/ooenergy/oiac003
11. Christian Troost, ..., Leila Niamir, et al.. 2023. How to keep it adequate: A protocol for ensuring validity in agent-based simulation. *Environmental Modelling & Software*. https://doi.org/10.1016/j.envsoft.2022.105559
12. Leila Niamir and Shonali Pachauri. 2023. From Social and Natural Vulnerability to Human-Centred Climate Resilient Coastal Cities. *Front. Sustain. Cities*. https://doi.org/10.3389/frsc.2023.1137641
13. Alessio Mastrucci, Leila Niamir, Benigna Boza-Kiss, Nuno Bento, Dominik Wiedenhofer, Jan Streeck, Shonali Pachauri, Charlie Wilson, Souran Chatterjee, Felix Creutzig, Srihari Dukkipati, Wei Feng, Arnulf Grubler, Joni Jupesta, Poornima Kumar, Giacomo Marangoni, Yamina Saheb, Yoshiyuki Shimoda, Bianka Shoai-Tehrani, Yohei Yamaguchi, Bas van Ruijven. 2023. Modelling low energy demand futures for buildings – Current state and research needs. *ARER*. [accepted]
14. Nuno Bento. 2023. Digital convergence and sharing in consumer goods for improving lives and reducing carbon emissions. *Global Environmental Change* [accepted]
15. Wiedenhofer Dominik; Akimoto Keigo; Godoy León María Fernanda; Grubler Arnulf; Min Jihoon; Mastrucci Alessio; Unlu Gamze; van Ruijven Bas; Boza-Kiss Benigna; Ünlü Gamze; Ju Yiyi; Jupesta Joni; Kim Yong-Gun; Moon Jongwoo; Krey Volker; Magalar Leticia; Norman Jonathan; Niamir Leila; Plank Barbara; Streeck Jan; Bento Nuno; Wiese Frauke; Verdolini Elena; Wilson Charlie; Hayashi Ayami; Pauliuk Stefan. 2023. A review of industry modelling and demand-side transformations for low energy and materials demand futures. *ARER*. [draft]
16. Roy, J., Some, S. 2022. E-Mobility for a Sustainable World: Unavoidable Automobility and Global South-North Perspectives. [draft]
17. Bianka Shoai-Tehrani, Gersende Chaffardon, Mathilde Gresset-Bourgeois, Jean-Baptiste Arnoux, Claire Fourdan, Gaelle Lestage, Emeric Benoni, Pascal Gibielle. 2023. Implications of Energy Sufficiency on the Path towards Carbon Neutrality: a Quantified Assessment on Electricity Demand, Material Demand and System Costs. *ERL - Focus issue on Technology and Global Change*. [draft]
18. Steinberger, Julia; Rao, Narasimha; Pachauri, Shonali (n.d.). Living well with low energy demand: Towards a political economy of energy sufficiency . *Global Sustainability*. GSUS-2022-0030 [draft]
19. Nuno Bento. 2023. L'histoire se répète-t-elle ? Leçons des transitions technologiques passées et des faux-départs de l'économie de l'hydrogène.. In : Kroichvili N., Simoncini N., (eds),

L'Hydrogène par les Sciences Humaines et Sociales, Université de Technologie de Belfort-Montbéliard, Belfort. [draft]

20. Nan Zhou, Nina Khanna, Jingjing Zhang, Hongyou Lu, Wei Feng, and Bo Shen. . Energy Demand Changes Induced by Technological and Social Innovations: A Review of Sectoral and Global Perspectives [draft]

These papers include direct reference to EDITS.

Papers are prepared directly under EDITS umbrella (e.g. the Buildings model mapping and the Industry models mapping), and by members, teams or smaller groups of EDITS colleagues.

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).*

RESEARCH ORGANIZATION AND 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**[10].

A central repository for papers and presentations is created in the online tool **Zotero**, as well as a list is curated on the Sharepoint.

[10] https://zenodo.org/, Key benefits: run by CERN's Data Centre; promotes Open Science; uploads are assigned a DOI); available version control; GitHub integration.

PART 4. OUTREACH

ONLINE PRESENCE

EDITS has set-up **public channels**: a central webpage (Figure 9): https://iiasa.ac.at/projects/edits a twitter account: https://twitter.com/EDITS_Community, and a Linkedin account: EDITS Network | https://www.linkedin.com/groups/14104139/

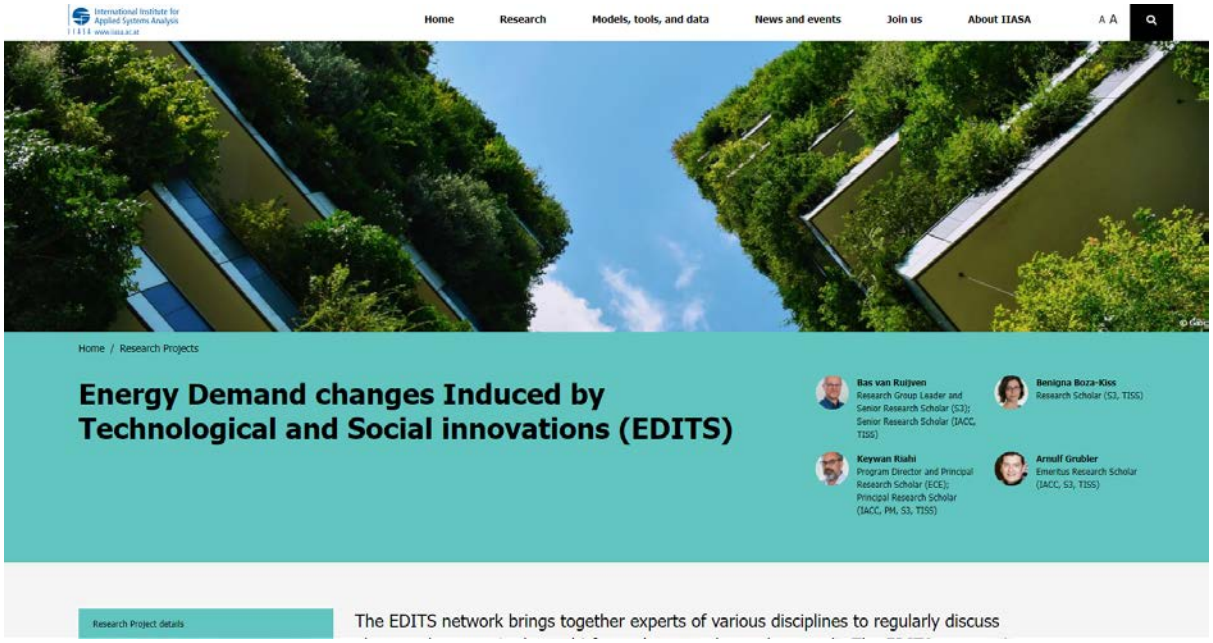


Figure 10. Central webpage

PUBLIC COMMUNICATION: WEBINARS

The Community felt the need to disseminate the results by teams, members, working groups. Therefore, a series of webinars have been started, coordinated by IIASA and European Institute on Economics and the Environment (CMCC-EIEE). The plan is to have 2-4 online webinars per year open for the public. In 2022 **two EDITS webinars** were held:

a. **Webinar #1:**
   Speaker: Nuno Bento
   Title: Promoting better lives is good for climate: potential co-benefits of digital convergence and sharing in consumer goods
   Time: Tuesday, 5 July 2022, 12:00 pm CEST
   Recording is available at https://www.youtube.com/watch?v=NjpU9zw04ak
b. **Webinar #2:**
   Speaker: Stefan Pauliuk
   Title: Reductions in material production induced by demand-side strategies: Implications for sustainable development
   Time: Wednesday, 15 September 2022, 12.00 pm CEST

EDITS-ARTS COMPETITION

The **EDITS-ARTS Competition** was organized to find alternative ways to describe a low energy demand scenario. EDITS called for submissions to imagine "life in 2050 with much less energy" into art, challenging positive-minded people to imagine a low energy future.

The winner of the first prize is **Futuregram2050**, who created a powerful 2-minute video to portray a positive transformative future and has clearly adhered to the three evaluation criteria. The production

has a compelling narrative that presents a balance between having access to modern technologies and services using modern digital solutions, while at the same time being also willing to limit the demand. Using an Instagram-like future magical ball, they tell us the story of people living in 2050, with much less energy and with competitions to lower individuals' impact on the environment using digital and circular solutions. The video can be watched at https://www.youtube.com/watch?v=OkzkY4SZeTo.

Other finalists were:

- Céline Keller: Somalia in 2050
- James Mckay: Yorkshire-in-2050
- Saher Hasnain: Attend
- Sally Cairns: Welcome to Heathrow
- Imagination Ignited: Haru Travels to 2050
- WEFEL: Geneva in 2050
- Stephanie Reiner: Life in 2050
- Jasmin Dobrovsky: My balkony 2050
- THE LAST SUPPER PROJECT: The last supper project
- Katarína Korytárová: Life in 2050

The evaluation was done by an EDITS committee**:**

- Keigo Akimoto, RITE;
- Joyee S. Chatterjee, AIT-EDITS;
- Poornima Kumar, CSTEP/University of Oxford;
- Masa Sugiyama, University of Tokyo;
- Elena Verdolini, University of Brescia and RFF-CMCC;
- Charlie Wilson, University of Oxford;
- Caroline Zimm, IIASA.

POLICY ENGAGEMENT

EDITS organized **two side-events at the COP27.** In November 2022, Egypt hosted the 27th Conference of the Parties of the UNFCCC (COP27) in Sharm El-Sheikh, with a view to building on previous successes and paving the way for future ambition to effectively tackle the global challenge of climate change. The vision of Egypt's COP27 presidency was to move from negotiations and planning to implementation, moving rapidly towards full, timely, inclusive, and at-scale action on the ground.

The first event took place on November 10, 2022, as an official side-event of the UNFCCC COP27. The high-level meeting addressed innovations for energy demand reduction, decarbonization of the urban environment and the construction sector, and pathways toward a net-zero society. The seminar was co-organized by the International Institute for Applied Systems Analysis (IIASA), the Research Institute of Innovative Technology for the Earth (RITE), and Development Alternatives (DA) under the umbrella of EDITS. More information and links to the presentations can be found at: https://iiasa.ac.at/events/nov-2022/edits-at-unfccc-cop27-high-services-with-low-energy-and-resource-demand-for-low

On 17 November 2022, the EDITS organized the event "High wellbeing with low energy demand towards a modern net-zero society" at COP27. The seminar discussed different aspects of

technological, social, and infrastructural innovations that can deeply reduce demand for energy and stimulate a just transition to net-zero societies. More information and links to the presentations can be found at: https://iiasa.ac.at/events/nov-2022/rite-iiasa-side-event-on-edits-at-unfccc-cop27

WIDER SCIENTIFIC ENGAGEMENT

EDITS has started to deliver **presentations and special seminars, side-events at other scientific conferences.**

For example, EDITS participated at the Summer Study of "European Council for an Energy Efficient Economy", the ECEEE Conference. A so-called informal session was organized and conducted with the title "Can we replicate frontrunner examples? Real-life social and technological innovations in buildings". The event took place on 10 June, Friday, between 14:00-15:00 with 15 participants.

EDITS participated at the Forum on Scenarios for Climate and Societal Futures (the Scenarios Forum), which was a hybrid online and in-person forum bringing together a diverse set of communities who are using or developing scenarios for use in climate change and sustainability analysis to exchange experiences, ideas, and lessons learned. The Parallel Session 70 on "Narratives for scenarios and pathways to provide decent levels of energy services at low demand of energy and resources" can be viewed at: https://www.youtube.com/watch?v=oVwSEXyTuGU.

PART 5. OUTLOOK FOR 2023-24

The EDITS Annual Meeting was an opportunity to develop plans and ideas for the next year of EDITS.

A brief qualitative summary of what was commented by the participants is provided here.
Value-added of EDITS and demand-side research was discussed.

- EDITS represents a novel and important complementary approach to supply side approach, which is so dominant in many countries.
- Bringing a demand-side focus in research, modeling and policy-making should be obvious for many reasons (including, but not limited to climate mitigation, SDGs, wellbeing, disruption management). Strong arguments are evident for us, and we need to push that further.
- Modelling improvement is clearly needed. There has been a lot done, and it is a strong community, but there is a long way to go. The IAM process is a good example to learn from.
- Linking bottom-up and top-down/IAM models is an important aspect of EDITS.
- EDITS reflects the modelling side of demand-side research, but it is clear that the qualitative element, i.e. narratives to imagining future outcomes is crucial. A demand-side research is incomplete without such , many details in narratives.
- The heterogeneity represented in EDITS is a good source for more insights.

Themes: All groups were enthusiastic about the themes dealt with at the meeting, and many highlighted certain areas for further discussion.

- It was valuable to explore the many rich connections between LED and SDGs; covering remaining SDGs.
- The focus on energy sufficiency is important. It was agreed that there is still significant confusion on the definitions.
- Broadening the progress indicator, going beyond GDP, building new scenarios
- Let's talk about policy measures: What are the actual leverage points/governance req. for LED? How can they be modelled to endogenously arrive at LED? Translating it into policy action?
- Multiple Co benefits from a LED angle is an exciting opening up of the current research streams.
- Fast track actions needed given time constraints- interdisciplinary cross pollination of ideas needed, knowledge products for progress indicators and scenarios.

Urgency, relevance and timeliness: It is time for action in demand-side from many perspectives.

- The current crises could put attention on demand-side options, yet the focus is (again) not strong enough.
- It was expressed that scenarios creation was time-consuming and relatively slow (broadly, not just in EDITS), whereas the pressures are high. There is a need for a more speedy solution.
- Strengthen bottom-up and broader sustainability perspective towards (1) AR7, esp. in transport, (2) national teams and public/policy discourse.
- We have at hand a lot of knowledge and methodological expertise, as well as access to data. At the same time, there is large gap still in all of these.
- Strategic constraints for talking about "over"-consumption.
- LED is more explicit in its "normative" assumptions and constraints than maybe the other SSPs.

Methodologically: There is a lot of knowledge and experience at hand, while we have to be careful in identifying the appropriate methodology for the work.

- The EDITS Community is diverse, and it is hard to constraint all approaches to a single narrative. At the same time this can be used for a well-enriched narrative development with lots of (local) details.
- Modell complementarity is really important!
- The fundamental direction for modelling human behavior could be set-up within EDITS
- Topic of sufficiency – conceptually acknowledged, model wise difficult to implement
- Feasibility of the scenarios that are developed need to be included in EDITS and WG Synthesis will look into that.
- Modeling the many potential benefits of LED pathways in own modeling work needs specific methods.
- Very different communities, perspectives enriching this narrative.
- Bad cop/good cop. More explicit focus on potential downsides, e.g. of digitalizations (someone called it "value neutral").

Community: A strong aspect of EDITS it's the networking and community development.

- The EDITS Community is supportive, and it was appreciated to be exposed to it and understand what it does.
- There is no shaming in the Community, and it is comfortable to discuss even hot potato topics
- It was nice to see a lot of new people
- Quality of team involved
- Value of constant base-level of team-work and collaboration.
- Hearing from different angles (e.g. LCA researcher hearing about IAMs, etc.)—diversity of perspectives. Enriching.
- To have the possibility to contribute beyond the mainstream

Suggestions for the next meeting:

- The organizers were happy to hear that the meeting resonated well with the participants, who considered the workshop overall fine/good/excellent.
- Participants suggested that main topics (mainly emerging ones) would benefit from preparatory framing, and thus more time would be available for deep discussion.
- While the overall mix of plenaries and free discussion was appreciated by many, it was to move the balance of plenaries and smaller group-meetings towards the latter by others, in order to ensure a more relaxed setting. It was thought that open-floor might create hesitancy for people to speak up; more avenues to raise ideas would allow for more inclusive discussion.
- Along the same lines, more working group time and working sessions would be appreciated.
- The poster session was well-received this year (as in previous years). There should be a dedicated poster session at future meetings, where participants could focus on the posters more. The topic of the poster session could also be more specific.
- Several participants prefer a latter start in the mornings and shorter hours to be more effective.
- Social events could be better linked to the theme, e.g. organize an event in the global south.
- The meeting should be opened for a wider participation, in particular for policy makers and media.

Where we want to be in February 2024

- Overview of EDITS organization:
  - EDITS should continue with the existing WGs

- Establish a new WG on Wellbeing
- Include extra streams, exemplified by the fast-tracks.
- Community plans to find ways to include members that are not well integrated in the current structure.
- Quarterlies are planned 3 times a year and the next Annual in 2023 is foreseen in Autumn 2023 in Lisbon, Portugal.
- Working Groups shall meet on-demand to ensure progress.

- Outputs:
  - Target number of paper is 15 by March 2024, and to achieve this:
    - 1. Follow-up on special topics after the sectoral review papers;
    - 2. Sectors and data gaps;
    - 3. Progress on low energy means scenarios;
    - 4. Fast-track papers.
- Outreach:
  - Webinars: continue and organize about 2-4 webinars per year
  - Outreach events, policy events: COP, G7 and local events
  - Research events: encourage presentation of results at scientific conferences
  - Social media set-up and population

ANNEX 1: EDITS ANNUAL MEETING 2022 SUMMARY

Brief summary of the dedicated discussion topics is provided.

How local can we go?

The session first discussed the role of EDITS research and where the community's focus should lie:

- ⇨ The **urgency** of the climate crisis along with a growing number of other pressures (wars, pandemic, economic and social distress, etc.) places more pressure on the research community to progress on filling in research gaps.
- ⇨ Today's challenges are **complex** that need a **systemic perspective**. A demand-side approach could better inform detailed, **human centric solutions**, yet it also needs to consider the systemic level, and provide an understanding of how much resources are needed for a decent level of well-being (in line with SDGs), respecting the Earth system boundaries, distributional aspects that reflect heterogeneity, beyond a national average representative consumer or household, and institutional/organizational variables that impact service delivery systems. It is important to emphasize that energy and resource demands themselves are intermediary variables.
- ⇨ There have been a number of **EDITS relevant-research** gaps identified by IPCC, such as better metrics to measure actual human well-being, evaluation of climate implications of the digital economy, scenario modelling of services, interactions between various drivers of change (social, structural, individual).
- ⇨ The strength of EDITS to build on in the future is its **cross sectoral nature and internationality**.
- ⇨ In Japan, EDITS is expected to **identify opportunities to reduce energy demand** to contribute to achieving GX, decarbonisation of local communities and people's lives. EDITS shall have an **international focus** on demand aspects, and have an important role in the **next cycle of the IPCC**, going beyond the coverage of demand in Sixth Assessment Report of the IPCC (AR6) WGIII.

The session discussed what is needed to make the global LED narrative relevant in the diverse subglobal context.

- ⇨ The **High with Low future (HWL)** narrative was explained and described (see Figure 4).
- ⇨ The HWL includes a **shift from input-oriented analysis** to **output and outcome oriented** (services and wellbeing) approach.
- ⇨ HwL places an emphasis on **services, people and well-being, highly distributed, decentralised approach** to imagining futures, inter-dependent behavioural, social innovation, institutional, and technological innovation. Instead of focusing on conversion efficiency and technical performance, HWL looks at service efficiency (device convergence). It's about how innovation changes behaviour, business models, institutions in totality.
- ⇨ Why HwL is important:
    - o 1. HWL taps potential for service-led transformation. Massive inefficiencies. One EJ saved cascades to much more at the other end of the chain.
    - o 2. HWL delivers well-being and developmental benefits.
    - o 3. HWL is self-reinforcing, accelerates, widely accessible: PVs, EVs, rapid increases in deployment rates. More granular, small-scale technologies and infrastructure more widely accessible.
    - o 4. HWL removes geoengineering (CDR) reliance. Lower environmental risks, focuses more on rapid demand reduction and high well-being instead. Lower environmental, developmental, implementation risks.
    - o 5. Feasibility once over near-term institutional and socio-cultural hurdles.
- ⇨ There are already scenarios that adapt the LED/HWL to local levels:

- **France** has developed sufficiency scenarios that are focused mostly on the short-term. E.g. heating reduction by 1°C to reduce energy demand, but not much about renovation, based on the notion of urgency of energy security.
- **Japan** has energy demand models for the Japanese buildings using an interesting case study on HWL, focused on tech innovation measures so far. 40% reduction needed is possible, but the speed is insufficient. HWL is a good bridge for this problem. The critical aspect of energy demand reduction in Japan is associated with the many social problems, e.g. aging population. To facilitate structural change in such situation, there is a need to explore synergies with other problems.
- A LED-scenario has also been developed by CSTEP for **India** in the SAFARI model that are close to HWL, DLS and innovation. DLS drives the model, which includes 100+ levers. In line with LED, scenarios with development goals can be met with low energy. This is possible with strategic interventions at the right time. Unique aspects – exploring cross sectoral impacts and unintended consequences of these. The model includes urban planning, and helps to reconcile local narratives with global narratives.

Special thanks go to:

- ⇨ Mariko Takatani (METI): for an opening speech and welcome
- ⇨ Keigo Akimoto (RITE), Bas van Ruijven (IIASA), Arnulf Grübler (IIASA): for an opening and welcoming
- ⇨ Arnulf Grübler (IIASA): for moderation
- ⇨ Charlie Wilson (University of Oxford): Kick-off presentation
- ⇨ Panelists: Albane Gaspard (ADEME), Yohei Yamaguchi (Osaka University), Kaveri Ashok (CSTEP), Roberto Schaeffer (COPPE)
- ⇨ Poornima Kumar (University of Oxford): for note-taking

Link to the recording is here.

How to sell a low energy demand scenario?

The session reviewed certain theories and experiences on both public and policy interaction with the low energy demand research community. It was discussed how to successfully present and communicate about LED scenarios, so that it motivates action, seems credible, and the audience understands and does not misunderstand.

- ⇨ The **naming** matters.
- ⇨ **Positive image of a LED future**: Creating a positive image of reducing demand with well being is central to communication, as well as informing the future impacts of not doing anything.
- ⇨ **Wording for different audiences:** Positive wording resonates better and tend to get more support. The French experience with *sobriété* however shows that it enabled public energy debate to advance to demand reduction discussions. Also normative, academic wording should be avoided to reach the general public. For policymakers, presenting scenario results with numbers works better.
- ⇨ **Strategy to enable demand change:** social media is an important tool to both inform that climate change is already happening and to communicate what we can do differently. It may seem that we can't compete with corporations power and resources to induce high demand, but it is important to create the political context that enables the demand reduction debate.
- ⇨ **Acceptability and willingness:** Belief that the strategy is effective to limit temperature leads to more acceptability of behavioral changes/demand reduction over technology change. Also concerns over climate emergency lead to more acceptability of LED scenarios. However, acceptability of LED narratives may be high, but not so much when description of scenarios are made in terms of lifestyle changes.

- ⇨ **Considering diversity and inequality:** cultural diversity and inequality should be considered when framing the message of demand-side transformations, since people in different contexts have different needs.

Special thanks go to:

- ⇨ Diana Ürge-Vorsatz (CEU): for moderation
- ⇨ Adriana Hernandez and colleagues (Futuregram): for presentation
- ⇨ Panelists: Linda Steg (University of Groningen), Felix Creutzig (MCC), Yves Marignac (NegaWatt), Joyashree Roy (AIT)
- ⇨ Marianne Zanon Zotin (Federal University of Rio de Janeiro): for note-taking

Link to the recording is here.

Multiple dimensions and benefits of demand side

We looked at the value of LED futures from a number of perspectives.

- ⇨ The High with Low scenario uses **Sustainable Development as entry point** with LED extension and selected **leverage focus (DSL, digitalization, innovation)** with higher spatial resolution than it was in LED. There is need to work further on HwL, to extend the impact assessment (water, land, air), and the implementation focus (cities, economy, infrastructures).
- ⇨ The ultimate goal of EDITS scenarios should be to create integrative scenarios, for which it is necessary to:
  - o develop operational concepts and measurements of wellbeing dimensions;
  - o develop representation/modeling of distributions
  - o explicitly consider planetary boundaries beyond climate
  - o include social and institutional dimensions (SDGs 4, 5, 16, 17)
  - o explore alternative pathways

- ⇨ **Multiple benefits** matter:
  - o **Health and productivity** are benefits at the local level instead of global benefits.
  - o **Active days gained** are in the range of 1-2.5 days for tertiary building improvements and 2-5 days gained for residential sector improvements.
  - o There is a strong linkage between **energy security** and the role of **energy demand reduction**, which are now contextualized due to Russia politics. Slashing energy demand would cut global emissions by 2.9% in 12 months and avert fuel shortages.
  - o However, energy poverty makes the energy access issue inelastic in energy demand to secure livelihoods.
  - o IPCC concluded that co-benefits and trade offs at the macroeconomic levels are underestimated and not accounted for in mitigation strategies. The key co-benefits were identified as **employment, trade and structural change**. Job creation is often higher from energy demand sectors.
  - o There is a need for **new indicators to assess mitigation impacts** on competitiveness / green structural change.

Special thanks go to:

- ⇨ Joyashree Roy (AIT): for moderation
- ⇨ Presentations by:
- ⇨ Arnulf Grübler (IIASA) Souran Chatterjee (Central European University), Felix Creutzig (MCC), Nuno Bento (University Institute of Lisbon, DINÂMIA-CET)
- ⇨ Joni Jupesta (RITE): for note-taking

Link to the recording is here.

Research-support sessions

The research support sessions were novel in their format and focus. This was a follow-up on calls for more linkages with existing research on the one hand, and to produce fast outputs besides longer-term, deep analyses.

Session 5. Fast-track proposals

To identify areas of interest that could quickly lead to interesting, but focused outputs a call for ideas was announced as a preparation for the Annual Meeting.
Bas van Ruijven presented a plan for supporting the fast completion of the fast-track initiatives. A person should volunteer to lead a small group of members to deliver a focused review/research/summary/novel outputs (e.g. blog, podcasts, etc.).
The leads pitched the idea at the Annual Meeting, and others could gather in dedicated meeting places to agree on the content, output type and timing. In the coming months, the EDITS coordination will help preparing for high-level journals. EDITS will be able to provide some seed funding to complete the well-progressing outputs based on the decision of a small committee.

The fast-track teams are expected to submit a first idea in one-pager shortly after the Annual Meeting, and showcase the progress at the Quarterly in December.

The following four proposals were submitted and presented:

- **Charlie Wilson**: Modeling digitalization
- **Masahiro Sugiyama, Tao Cao, Yiyi Ju, Bas van Ruijven**: Improved demand-side modeling for high levels of well-being and low energy and materials.
- **Sascha Nick**: Ensuring negative emissions benefit society
- **Benigna Boza-Kiss and Nuno Bento**: security of services and low energy demand

Special thanks go to:

- ⇨ Joni Jupesta (RITE): for moderation
- ⇨ Presentations and note-taking by: Charlie Wilson (University of Oxford), Masahiro Sugiyama (University of Tokyo), Sascha Nick (EPFL), Benigna Boza-Kiss (IIASA), Nuno Bento (DINÂMIA-CET)

Link to the recording is here.

Session 6. Research presentations of the community

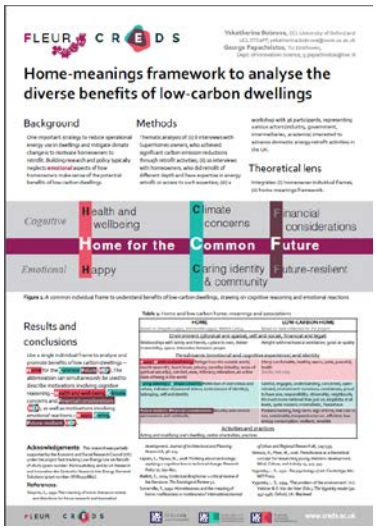
The EDITS activities are closely linked to the usual research interest of the members. The value of EDITS lies in combining running research in a broader perspective and find new concepts, novel ideas, reformulated methods. This session showcased on-going internal research of the members that are relevant for the whole community. 11 speakers presented their research in flash-talks in 3 minutes each, followed by posters in the Ovaler Saal that allowed for further discussion over coffee and drinks.

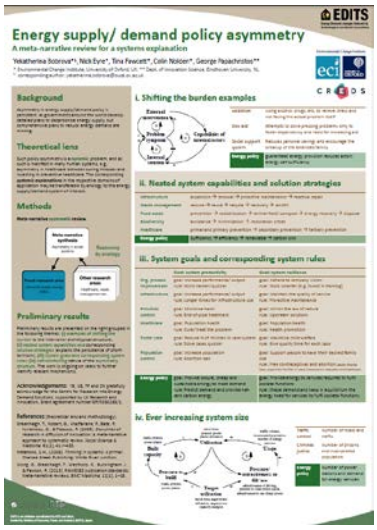
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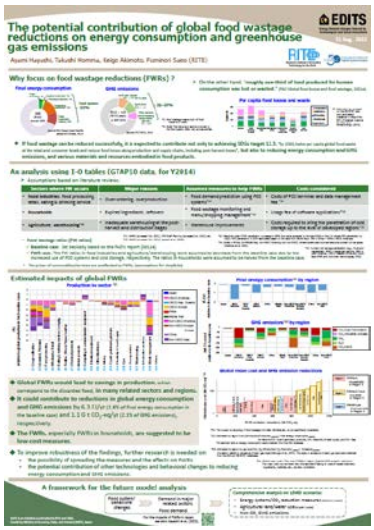
The list of presenters:

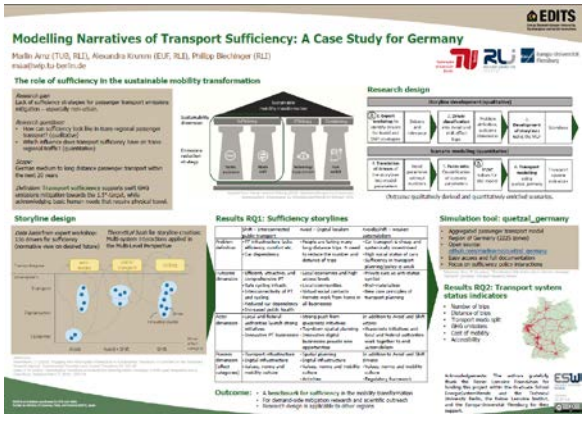
1. **Yekatherina Bobrova**, George Papachristos (Uni of Oxford, Eindhoven University)
2. **Yekatherina Bobrova**, Nick Eyre, Tina Fawcett, Colin Nolden, George Papachristos (Uni of Oxford, Eindhoven Uni)
3. **Ayami Hayashi**, Takashi Homma, Keigo Akimoto, Fuminori Sano (RITE)
4. **Arnz Marlin**, Alexandra Krumm, Philipp Blechinger (Technical Uni. Berlin; Uni. Flensburg; RLI)
5. **Sascha Nick**, Joel Millward-Hopkins, Julia Steinberger, Philippe Thalmann (EPFL, University of Lausanne)
6. **Sascha Nick**, Philippe Thalmann (EPFL)
7. **Bianka Shoai-Tehrani**, Gersende Chaffardon, Jean-Baptiste Arnoux, Gaëlle Lestage, Emeric Benoni, Pascal Gibielle (RTE)
8. **Johannes Thema**, (Wuppertal Institute for Climate)
9. **Yohei Yamaguchi**, Hideaki Uchida, Yoshiyuki Shimoda (Osaka University)
10. **Caroline Zimm**, Paul Kishimoto, Setu Pelz (IIASA)
11. **Hara Takuya** (IIASA, Toyota)
12. **Naoko Onishi**, Joni Jupesta, Fuminori Sano, Keigo Akimoto (RITE) [online]
13. **Albane Gaspard** (ADEME) [online]

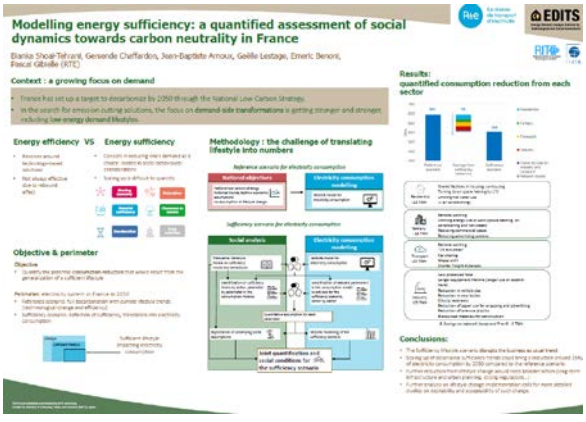
The posters – available as pdf here.

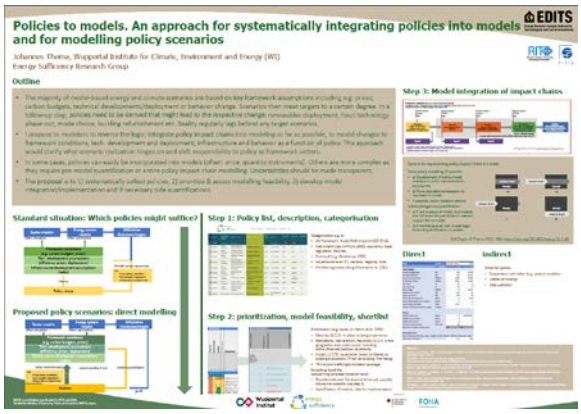


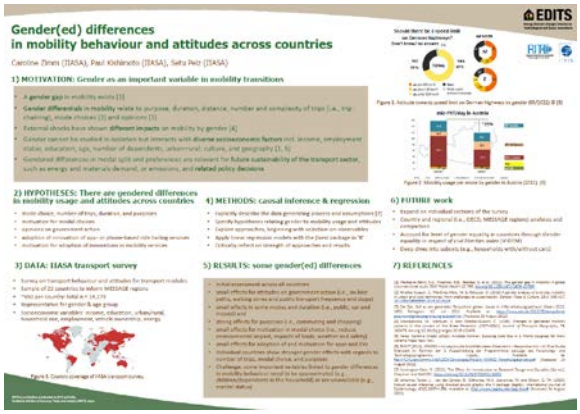


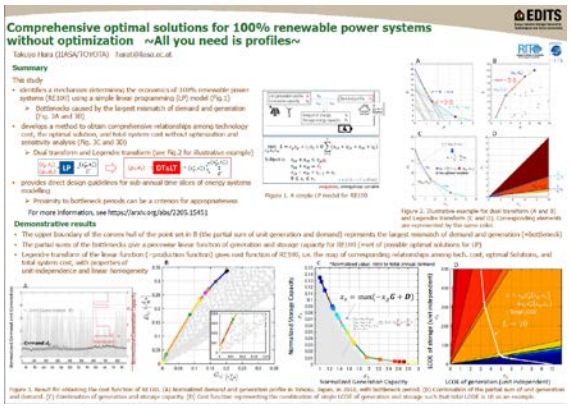


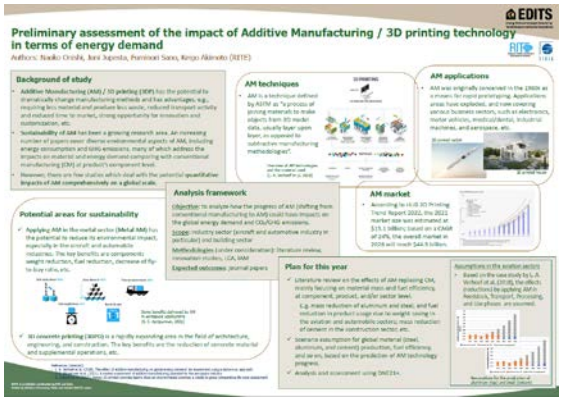


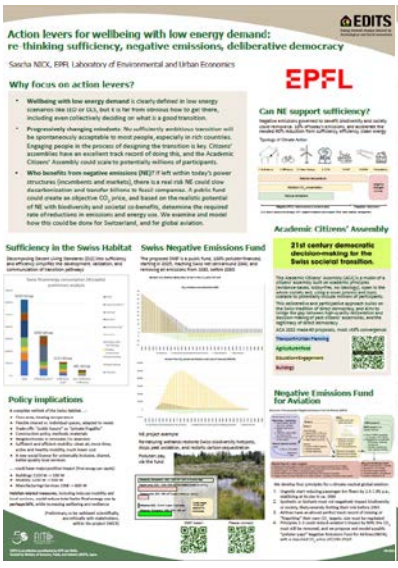


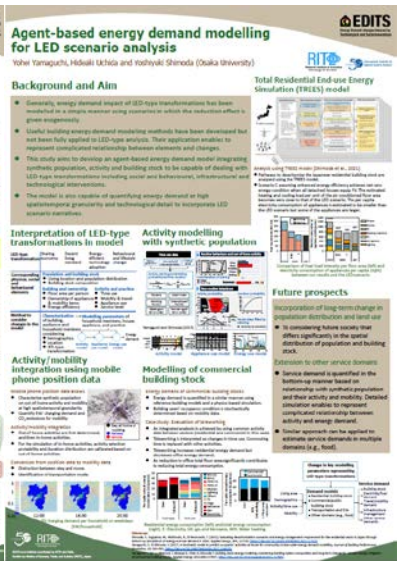

Policies to models. An approach for systematically integrating policies into models and for modelling policy scenarios
EDITS
Johannes Therne, Wuppertal Institute for Climate, Environment and Energy (WI)
Energy Sufficiency Research Group
Outline
Standard situation: Which policies might suffice?
Step 1: Policy list, description, categorisation
Step 2: prioritization, model feasibility, shortlist
Proposed policy scenarios: direct modelling
Direct
Indirect
FOHA


Gender(ed) differences in mobility behaviour and attitudes across countries
EDITS
Caroline Zimm (IIASA), Paul Kishimoto (IIASA), Satya Petr (IIASA)
1) MOTIVATION: Gender as an important variable in mobility transitions
2) HYPOTHESES: There are gendered differences in mobility usage and attitudes across countries
3) DATA: IIASA transport survey
4) METHODS: causal inference & regression
5) RESULTS: some gender(ed) differences
6) FUTURE work
7) REFERENCES


Comprehensive optimal solutions for 100% renewable power systems without optimization ~All you need is profiles~
EDITS
Takuto Hara (IIASA/TOYOTA) hara@iiasa.ac.at
Summary
Demonstrative results


Preliminary assessment of the impact of Additive Manufacturing / 3D printing technology in terms of energy demand
EDITS
Authors: Naoko Onishi, Joni Jupesta, Panmisol Sono, Keigo Akimoto (RITE)
Background of study
AM techniques
AM applications
Analysis framework
AM market
Potential areas for sustainability
Plan for this year


Action levers for wellbeing with low energy demand: re-thinking sufficiency, negative emissions, deliberative democracy
EDITS
Sascha Nick, EPFL Laboratory of Environmental and Urban Economics
Why focus on action levers?
Can NE support sufficiency?
Academic Citizens' Assembly
Sufficiency in the Swiss Habitat
Swiss Negative Emissions Fund
Negative Emissions Fund for Aviation
Policy implications


Agent-based energy demand modelling for LED scenario analysis
EDITS
Yohei Yamaguchi, Hideaki Uchida and Yoshiyuki Shimoda (Osaka University)
Background and Aim
Total Residential End-use Energy Simulation (TREES) model
Interpretation of LED-type transformations in model
Activity modelling with synthetic population
Future prospects
Activity/mobility integration using mobile phone position data
Modelling of commercial building stock


Introducing sufficiency in scenarios for the building sector: insights from France
EDITS
ADEME Transition(s) 2050 scenarios
Key questions
Method
Results
Conclusion
https://transitions2050.ademe.fr/en

ANNEX 2: EDITS ANNUAL LIST OF PARTICIPANTS

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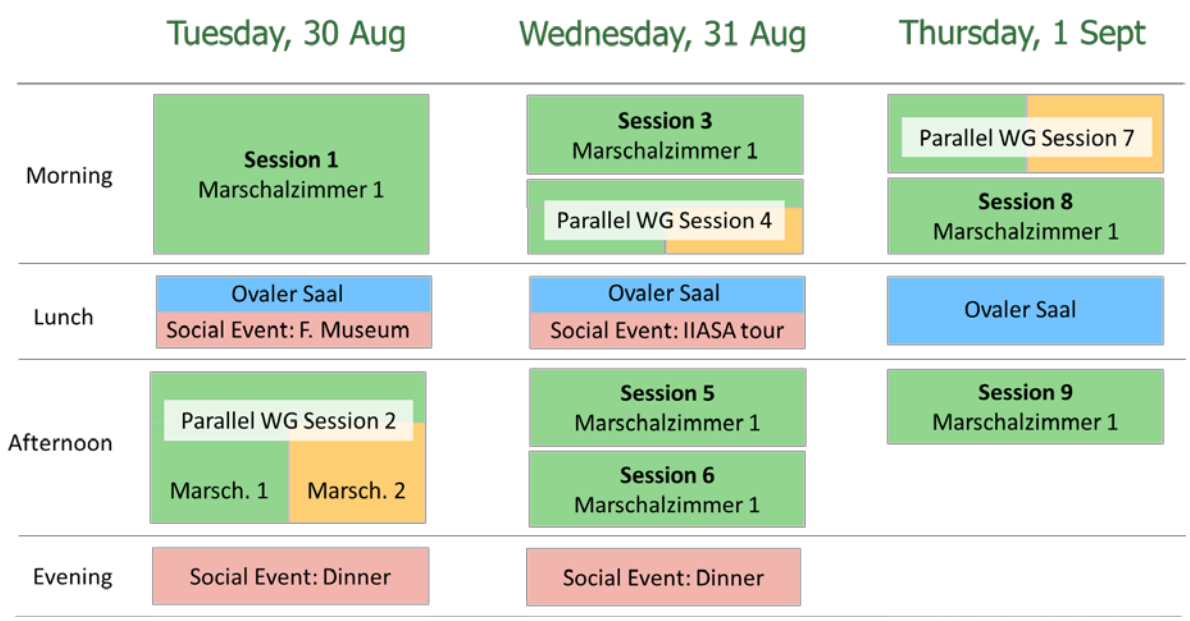
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ANNEX 3: EDITS ANNUAL AGENDA AND PROGRAM

Session overview



Program [all times in CEST]

August 29, Monday Optional side-event by WG Data

12:00 **Shuttle bus** pick-up from Vienna

12:30 Coffee and light lunch

13:00-17:00 Side-event for Working Group 2 Data Gvishiani room

13.00: Introduction round, collecting ideas and interest

13.30: Presentation of the datagaps review structure

14.00: Interactive discussion by working on few clear illustrative examples + formulate next steps review paper

15.00: Coffee Break

15.30: Presentation of the *demand side innovation* paper

16.00: Discussion with group

17.00: Adjourn

17:30 Shuttle bus back to Vienna

DAY 1 - August 30, Tuesday

10:00 **Shuttle bus** pick-up from Vienna

10:30-11:00 Arrival and registration / welcome coffee

11:00-13:00 Session 1. How local can we go? Marshallzimmer 1

Moderator: **Arnulf Grubler**, IIASA (Austria)

The session will open the 2022 EDITS Annual Meeting and it will recall the founding ideas of EDITS. We will review global and sub-global understanding of the LED scenario, including a presentation of the new High-with-Low scenario narrative. A panel of experts, with the involvement of the audience, will debate the influence of local context in specifying sub-global and national LED narratives.

11:00-11:20 Welcome and goals of the meeting

Keigo Akimoto, RITE (Japan) and **Bas van Ruijven**, IIASA (Austria)

11:20-11:30 Achieving Green Transformation (GX) and the importance of demand side

Mariko Takatani, METI (Japan)

11:30-13:00 Presentation of "the High-with-Low narrative"

Charlie Wilson, University of Oxford (UK)/ IIASA (Austria)

Panelists: **Albane Gaspard**, ADEME (France), **Yohei Yamaguchi**, Osaka University (Japan), **Kaveri Ashok**, CSTEP (India), **Roberto Schaeffer**, COPPE (Brazil)

General discussion on:

- What is the new High with Low narrative?
- How to transfer global low energy demand narratives to sub-global contexts
- What are essential differences between countries that modify the local LED-versions?
- Challenges for translating the High-with-Low narrative into modelling protocols

13:00-14:00 Lunch break **Ovaler Saal**

14:00-16:00 Visit to Franzensburg in Schlosspark Laxenburg

16:00-18:30 Session 2. Parallel Working Group sessions

The Parallel Working Group sessions are tailored to the current working stage of each group. Participants can join any of the parallel sessions, contribute to on-going or emerging tasks, but can also use the time to socialize and/or organize other specific research ideas in the scope of EDITS (e.g. fast tracks).

Note Session 2. starts with a common general part on the narrative, followed by two WG-specific parallels.

16:00-17:10 Session 2.a. Working Group 3 – Narratives Marshallzimmer 1

Co-leads: **Arnulf Grubler,** IIASA (Austria) and **Charlie Wilson,** University of Oxford (UK)/ IIASA (Austria)

Session content:

- **Charlie Wilson**: presentation of High with Low narrative.
- **Arnulf Grübler**: quantifying consistent demands using the DETRAS framework.
- Round table comments by chairs of working groups (buildings, transport, industry) and discussion mainly on buildings narratives

Preparation: You can find the High-with-Low narrative here, and the DETRAS here.

17:15-18:30 WG-Parallels

Session 2.a. continued Working Group 3 – Narratives Marshallzimmer 1

Co-leads: **Arnulf Grubler,** IIASA (Austria) and **Charlie Wilson,** University of Oxford (UK)/ IIASA (Austria)

Session content:

- General discussion focused on transport and industry

Session 2.b. **Working Group 1 – Buildings** **Marshallzimmer 2**

Co-leads: **Alessio Mastrucci**, IIASA (Austria) and **Leila Niamir**, IIASA (Austria)

Session content: Planning and drafting of the next working phase. The pre-submitted topics will be presented by members in 5 minutes each. These research ideas will be further developed at the spot, leading to an extended outline and list of interested contributors.

Preparation: Please submit ideas that you are willing to commit to in this survey.

18:30-21:00 Adjourn and departure to Social Event

18:30 **Shuttle bus** from Laxenburg to Vienna

19:00-21:00 **Dinner at Stöckl im Park** (Prinz Eugen Straße 25 A - 1030 Wien)

DAY 2 - August 31, Wednesday

08:00 **Shuttle bus** pick-up from Vienna (see Logistic Note for location map)

09:00-10:30 Session 3. How to sell a low energy demand scenario? Marshallzimmer 1

Moderator: **Diana Ürge-Vorsatz**, Central European University (Austria/Hungary)

The session will discuss experience and scientific evidence on how to communicate about complex solutions such as energy system transformation through energy demand reduction. We will talk about the differences in the framing in different regions, countries or communities. We will differentiate communication strategies depending on the target audience, such as the public, fellow researchers, or policy makers. There will be showcases of different media, including social networks that have proven effective in energy demand communication.

09:00-09:15 Winners of the Arts Competition and the story of the video

Adriana Hernandez, Futuregram (Austria)

09:15-09:25 Public support for mitigation options and pathways

Linda Steg, University of Groningen (the Netherlands)

09:25-09:35 Using social media to communicate about energy demand

Felix Creutzig, MCC (Germany)

09:35-09:45 Influencing policy through successful communication about sufficiency, the French example

Yves Marignac, NegaWatt (France)

09:45-09:55 Global South perspectives on communicating low energy demand scenarios

Joyashree Roy, AIT (Thailand)

09:55-10:30 General discussion on:

- What is the message that can be well-received by the general public?
- Who needs to pick up the message?
- Is the message location specific?

10:30-11:00 Coffee break

11:00-13:00 Session 4. Parallel Working Group sessions

The Parallel Working Group sessions are tailored to the current working stage of each group. Participants can join any of the parallel sessions, contribute to on-going or emerging tasks, but can also use the time to socialize and/or organize other specific research ideas in the scope of EDITS (e.g. fast tracks).

Note Session 4. starts with a common general part on the protocol, followed by two WG-specific parallels.

11:00-11:55 Session 4.a. Working Group 3 – Model complementary protocol Marshallzimmer 2

Co-leads: **Masahiro Sugiyama**, University of Tokyo (Japan) and **Bas van Ruijven**, IIASA (Austria)

Session content: Presentation of the protocol testing phase and proposal of the process for the complementarity exercise. The group will discuss the indicator list and the process to be followed. We will have detailed discussions in three smaller groups: industry and buildings, with transport integrated into Session 4.b. Deadlines, tasks and activity lists will be discussed.

Preparation: Please comment on the list of variables here. See instructions in Masa's email ("Survey on the model complementarity exercise," May 16).

ca. 12:00-13:00 WG-Parallels

Session 4.a. continued Working Group 3 – Model complementary protocol Marshallzimmer 2

Co-leads: **Masahiro Sugiyama**, University of Tokyo (Japan) and **Bas van Ruijven**, IIASA (Austria)

Session content:

- General discussion focused on buildings and industry

Session 4.b. Working Group 1 – Transport Marshallzimmer 1

Co-leads: **Luis Martinez**, OECD-ITF (France) and **Paul Kishimoto**, IIASA (Austria)

Session content: It will be partially a break-out group of Session 4.a. on WG Protocol and partially a WG Transport Session.

The currently on-going paper draft will be extended and sub-sections will be discussed in small groups. The aim is to finish the draft of the paper soon after the meeting, therefore specific responsible parties will be identified for sub-chapters and draft contents will be reached by the end of this session.

13:00-14:30 Lunch break Ovaler Saal

14:30-15:15 Session 5. Fast-track proposals Marshallzimmer 1

Moderator: **Joni Jupesta**, RITE (Japan)

To boost visibility of EDITS and demand side research in general, it was decided at the 1st EDITS Quarterly 2022 that the Community would like to aim for outputs that are very specifically targeted and produced quickly in a concerted manner. Proposals will be presented and discussed.

15:15-17:30 Session 6. Research presentations of the community Marshallzimmer 1/Ovaler S.

Moderator: **Joni Jupesta**, RITE (Japan)

The EDITS activities are closely linked to the usual research interest of the members. The value of EDITS lies in combining running research in a broader perspective and find new concepts, novel ideas, reformulated methods. This session will showcase on-going internal research of the members that are relevant for the whole community.

Speakers can present their research in flash-talks in 3 minutes each, followed by posters in the Ovaler Saal and further discussion over coffee and drinks.

18:00-21:15	**Adjourn and departure to Social Event**
18:00	**Shuttle bus** from Laxenburg to Gumpoldskirchen/Thallern
18:30-19:15	Walk in the vineyards (depending on the weather)
19:15-21:15	**Dinner at Krug** (Kirchenplatz 1, 2352 Gumpoldskirchen)
21:15	**Shuttle bus** from Gumpoldskirchen to Vienna

DAY 3 - September 1, Thursday

08:00 **Shuttle bus** pick-up from Vienna (see Logistic Note for location map)

09:00-11:00 Session 7. Parallel Working Group sessions

The Parallel Working Group sessions are tailored to the current working stage of each group. Participants can join any of the parallel sessions, contribute to on-going or emerging tasks, but can also use the time to socialize and/or organize other specific research ideas in the scope of EDITS (e.g. fast tracks).

Note Session 7.b. might be shorter, thus some timing adjustment may happen, which will be communicated at the spot.

Session 7.a. Working Group 1 – Industry **Marshallzimmer 2**

Co-leads: **Dominik Wiedenhofer**, BOKU (Austria) and **Stefan Pauliuk**, University of Freiburg (Germany)

Session content: We will discuss and refine the results of the second round of literature collection & coding, with contributions from all co-authors. Remaining gaps in the model family overview and in the literature will be identified and responsibilities will be assigned as well as additional experts to be invited to contribute. We will discuss the existing structure & content of the review draft and prepare the detailed roadmap for the next WG meeting in October/November.

Preparation: Please check the to do list for the industry modelling review, available in the sharepoint sheet 'Workflow_Workspace'.

Session 7.b. Working Group 3 – Synthesis **Marshallzimmer 1**

Co-leads: **Shonali Pachauri**, IIASA (Austria) and **Massimo Tavoni**, CMCC (Italy)
with presentation by **Elina Brutschin**, IIASA (Austria)

Session content: This session will present a theoretical framework for well-being/ feasibility analysis, discuss potential methodologies to derive key indicators of different well-being dimensions, and seek feedback from the EDITS consortium on the selected indicators and the potential to provide the model outputs/ variables required to construct these indicators.

11:00-11:30 Coffee break

11:30-13:00 Session 8. Multiple dimensions and benefits of demand side Marshallzimmer 1

Moderator: **Joyashree Roy**, AIT (Thailand)

We will assess the differences in understanding the multiple benefits of demand-driven energy system transformation and how these can be modeled. We will discuss limitations and what is needed to overcome them.

11:30-11:40 LED and the SDGs

Arnulf Grübler, IIASA (Austria)

11:40-11:50 Multiple benefits of energy demand on productivity and health

Souran Chatterjee, Central European University (Hungary)

11:50-12:00 LED and energy security

Felix Creutzig, MCC (Germany)

12:00-12:10 Macroeconomic multiple impacts

Nuno Bento, University Institute of Lisbon, DINÂMIA-CET (Portugal)

12:10-13:00 General discussion on:

- What multiple impacts are the most important to be incorporated into the discussions/models?
- How to communicate multiple impacts?
- How to model multiple impacts?

13:00-14:00 Lunch break

14:00-15:00 Session 9. Closing plenary with break-out groups Marshallzimmer 1

Moderator: **Benigna Boza-Kiss**, IIASA (Austria)

Break-out groups to discuss the results of the Annual Meeting and to set out plans for the next year.

Closing and Adjourn by IIASA (Austria) and RITE (Japan)

15:00 **Shuttle bus** to Vienna (see more in Logistic Note)

Modeling the direct energy use of internet data communication networks

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Abstract

The digitalization of the energy system and its end use services requires increasing data demands on the internet. This project focused on the energy use associated with the communication networks that transmit data between data centers and end user devices, which currently account for between 1% and 2% of global electricity use. More specifically, this project aimed to provide energy demand modelers with an understanding of major communication network system components, their energy use characteristics, and best-available data on overall energy demand for potential inclusion in energy demand systems models moving forward. To accomplish these goals, a literature review was performed to assess modeling approaches and data compilation was conducted for use by modelers. Additionally, recommendations for future work to improve the accuracy and granularity of network energy models are provided, which could enable future energy systems and integrated assessment models to explicitly account for the potential network energy use associated with increasing energy system digitalization.