令和５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６年３月

公益財団法人 地球環境産業技術研究機構

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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、２０２２年に行われたＣＯＰ２７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である。

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、２０２０年１１月に、ＣＯＰ２６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、パリ協定のルールにもとづく、プレッジ＆レビューの運用が本格化してきている。２０２３年は、第１回グローバルストックテイクが実施され、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、議論が深まった。

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ている。

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状況であり、第７次評価サイクルに向けて、気候変動に関する最新の科学的知見の提供が求められている。従って、環境と成長の好循環を実現すること、加えてＩＰＣＣの要請に対して我が国が積極的に貢献していくためにも、需要サイドの技術革新や社会変革がもたらすエネルギー需要の変化について、定量的かつ包括的に分析をインプットしていくことは極めて重要である。

本事業では、最新の科学的知見や国際交渉の動向も踏まえながら、①エネルギー需要サイドの技術革新と、②それに基づき生じる社会変化、③さらにそのＣＯ２排出削減への影響等について調査、分析、評価を行うとともに、④各国の主要研究機関と共に当該シナリオに対する比較研究を行った。これらにより、国際的な研究コミュニティにおいて主要な気候変動シナリオの位置づけを主流化していくことに

加え、ＩＰＣＣの報告書へインプットしていくことを目的として実施した。

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、大学等と共に以下の通り、需要サイドの変化に関連する複数の研究を行い、エネルギー需要サイドの変化について、比較分析、評価を行った。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。（下記の研究機関報告書一覧のうちの⑫東京大学の報告を主に参照）

（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、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について、G7 札幌コミュニケでも言及されている、”Avoided emissions（削減貢献量）”の視点にも焦点を当てつつコンピュータモデルを用いた包括的かつ定量的な分析・評価を行った。

②米国のローレンスバークレー国立研究所 (LBNL)は、少ないエネルギー需要で高いウェルビーイングを達成するための十分性をモデル化し、実装した。また、野心的な緩和策を実施するための情報ギャップを埋めるには、何がどのようなコストで機能するかを評価した。

③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における重要なデータのギャップを特定するためのデータマッピングを実施した。部門を超えた取り組みで、戦略、手法、地域にわたってマッピングされ、データギャップを示し、将来の需要側調査のロードマップを提供した。

④ブラジルのリオデジャネイロ連邦大学(COPPE) は、ブラジルの気候変動目標を達成するために、ブラジルの運輸部門におけるディーゼル需要の削減がもたらす影響を取りまとめた。道路の舗装状況とエコドライブの実践が高速道路でのディーゼル燃料消費にどのような影響を与えるかを調査することで、需要側に焦点を当てた。

⑤タイのAITは、モビリティ形成の触媒としての政策と発展途上国のセクター移行についてまとめた。
また、急成長するバングラデシュを例にアジア太平洋における最新のエネルギーサービスへのアクセスとエネルギー利用効率を分析し、移行の加速するために何に焦点を当てるべきかを検討した。

⑥中国の清華大学は、以下を含む中国のアンモニアエネルギーの二酸化炭素排出量と経済分析を行った。水素燃料補給所、アンモニア燃料供給所、発電所などの適用シナリオの下で、中国のアンモニアエネルギーの全産業チェーンの段階的なライフサイクル二酸化炭素排出量分析を実施し、アンモニアエネルギーの炭素排出レベルの分析に焦点を当てた。

⑦ポルトガルのリスボン大学研究所は、エネルギー安全保障のための需要側政策の活用、デジタルコンバージェンスと消費財の共有が生活環境を改善し、排出量を削減する可能性、またグループ活動に関する報告と作業計画案をまとめた。

⑧英国のプリマス大学は、ファストトラック（FT）として、少ないエネルギー需要で高い幸福度を実現：グローバル・サウスを建物についてモデル化して生活水準の説明変数を分析した。また、エネルギー移行のバランスとして、グローバル・サウスにおける適正な生活水準と将来のエネルギー需要の評価を行った。さらに、低エネルギー消費による高い幸福度を実現するインドの住宅向けシナリオについてまとめた。

⑨ハンガリーの中央ヨーロッパ大学(DBH)は、EUの建築部門におけるネットゼロとエネルギー自立への移行を達成するための道筋をまとめた。主に高効率ビル（HEB）エネルギーモデルを利用して、欧州連合（EU）加盟国ごとに分類したビルのエネルギー効率向上に関する将来の見通しを示した。

⑩韓国の延世大学・国際経済協会(KIEA)は、低エネルギー需要シナリオの分析である気候変動の影響評価によるCGEと指数分解について説明を行った。3つのシナリオを使い、韓国の人口変動とエネルギー集約度が温室効果ガス排出量削減にどのように影響するか分析した。

⑪米国のスタンフォード大学は、EMF37(北米の脱炭素化(deep decarbonization)と高電化シナリオ)の一次的なシナリオ分析およびEDITSのHwLシナリオの最終的なモデル比較を目的、実行、結果で示した。需要側のテクノロジー、行動、および政策をより重視した2つのシナリオの共通点および、今後の最新推奨事項で締めくくった。

⑫東京大学は、気候変動緩和のための需要側イノベーションに関する各モデルの特徴を活かしたモデル分析比較を実施した。2022 年にモデル相補性試算（MCE: Model Complementary Exercise）プロトコルを開始し、4つのシナリオ（気候目標とHwLナラティブの相互調整された組み合わせ）と3つのセクター（産業、住宅および商業、運輸）をカバーする13のモデルからシナリオデータを収集

し、活動-構造-強度フレームワークとKaya恒等式分解に基づいていくつかの予備分析を行った。

⑬英国のオックスフォード大学は、デジタル化がエネルギーと排出量に及ぼす間接的な影響の証拠をまとめた。エネルギー削減の可能性だけでなく、需要の反動や誘導によって観察された増加にも焦点を当て、デジタル化がエネルギー使用に及ぼす定量的な影響を分野ごとに最新の範囲で提供した。

⑭オーストリアのBOKU は、物質循環、産業、サービスの提供: 低エネルギー・物質需要のモデリングとシナリオのレビューを行った。また、産業モデリングのレビューとして低エネルギー・物質需要シナリオ調査結果を基に、世界中の適正な生活水準を実現するための物質ストックについて説明した。

⑮イタリアのCMCC は、イタリアの高周波スマートメーター電力データに基づく、ヨーロッパのエネルギー危機とそれに伴うエネルギー価格ショックによる家庭用エネルギー需要の影響の定量化の分析を行った。また、多次元フレームワークを使用した LEDM シナリオの統合を行った。さらに、物質循環、産業、サービスのプロビジョニングとして、低エネルギーと物質需要のモデリングとシナリオのレビューを行った。

⑯フランスのITF-OECD は、トランスポートにおける将来の低エネルギー需要のモデル化について現状と研究ニーズを説明し、EDITS ネットワーク内の活動の概要をまとめた。また、都市旅客輸送の脱炭素化に向けた世界的な軌道: 政策ベースのモデリングアプローチ、都市間および長距離旅客旅行の脱炭素化経路のモデル化、世界的な貨物の脱炭素化経路のモデル化、さらに、輸送の持続可能性の再考: ITF PASTA グローバル フリート モデルからの洞察、また持続可能なモビリティにおけるシェアードモビリティの役割を過去・現在・未来別にまとめた。

⑰スイス連邦工科大学ローザンヌ校 (EPFL)は、低リソース使用と高いウェルビーイングの両方を満たすデマンドサイドのアプローチを体系的に探索およびモデル化する目的で、EDITSの活動の中で議論された、エネルギー需要の削減がウェルビーイングに与える影響についての理解および指数、評価方法などをまとめた。

⑱オランダのフローニンゲン大学は、低炭素ライフスタイルが生活の質に及ぼす影響の評価を行った。多くの需要側の変化が実施される将来の生活がどのようになるかを示すシナリオを人々がどのように評価するかを調査することを目的とした。

⑲大阪大学は、日本を対象に開発してきた家庭部門エネルギー最終需要モデルを海外版に拡張した。エネルギー需要推計の基礎データである気象データ, 人口・世帯構成に関するデータを整備した結果を報告し、新規に開発したセントラル暖房システムの計算モジュールについて説明した。

⑳米国のウィスコンシン大学マディソン校は、社会革新により、エネルギー需要の低い未来が実現できるこ

と、また、技術革新により低コストで気候変動緩和が可能になることを解説した。さらに「High-with-Low」シナリオのナラティブな主要テーマ、部門横断的関連、及びモデリングへの影響をまとめた。

㉑オーストリアのIIASA は、活動、成果、科学的結果の概要を含めた作業方法、研究コミュニティの構築について、また2023 年 3 月から 2024 年 2 月までの EDITS ネットワークの調査およびモデリング活動に関する報告、及び、建築セクター モデリング ツールにおける LED 表現の現状に関する解説、期間中のエンゲージメントとアウトリーチの取り組みについて説明し、最後に今後の方向性に関する展望を記した。

㉒米国のカリフォルニア大学は、エネルギー需要モデルにおけるデータセンターと人工知能のインフラストラクチャのエネルギー使用を評価するための利用可能な最良のデータとモデリングアプローチのレビューをまとめた。

㉓OpenExpは、今世紀末までに気温1.5℃を目標とするIPCC AR6 SPMの地球規模の気候緩和経路における十分な可能性を活用するための政策をとりまとめた。

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

（３）ＩＰＣＣ報告書へのインプット

（２）で行った調査、分析、評価について、学会や国際会議での発表や論文の執筆等を行った。加えて、ＩＰＣＣ第６次及び第７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3名、代表執筆者13名、WG3 SPM執筆者11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）（今回のワークショップ欠席）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、その他、第5章代表執筆者のGregory Nemet氏、Julia Steinberger氏（今回ワークショップ欠席）もEDITS事業に貢献している）。

EDITS関係者の一部は、2023年11月にイタリアで行われた、IPCCのシナリオ分析に重要な役割を果たしてきた、Integrated Assessment Model Consortium (IAMC)の年次会合等にも出席し、次期IPCC報告書への情報インプットに対する活動を実施した。また、COP28の日本パビリオンでのサイドイベントも開催し、学術界、政策担当者への情報発信をし、次期IPCC報告書へのインプットの布石と

した。

（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ポルトガルのリスボンにある Iscte – リスボン大学研究所で開催し、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。

また、ワーキング グループおよびファストトラック（FT）ストリームの一環として、小規模チームによるオンラインで多数（60 回以上）の会議が年間を通じて行われ、四半期ごとに少なくとも 2 ～ 3 回の大規模なオンライン会議も行われ、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。

国際ワークショップ(年次会議)の詳細については次頁以降に示す。

2023 Annual EDITS Meeting
Improving wellbeing while avoiding dangerous climate change
2023年 11月7日～11月9日

背景

EDITS（Energy Demand changes Induced by Technological and Social innovations）事業では、2019 年に開始し、それ以来、専門家の有機的なネットワークに発展し、専門家が協力して世界的かつ詳細なレベルでの技術、社会、インフラの相互作用、およびそれらとウェルビーイングおよび SDGs との関係を基に、需要主導型のエネルギーシステム、エネルギーおよび素材需要予測についての理解を深めてきている。 EDITS は、国際的な研究協力によって、需要側ソリューションとエネルギーシステム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機会を特定するため、研究を実施している。

2023 年年次総会 EDITS は、地球環境産業技術研究機構（RITE)、国際応用システム分析研究所（IIASA)、およびリスボン大学研究所（ISCTE）の共催で開催された。

私たちは緊急の時代に生きている。 2023 年に発表された IPCC 統合報告書は、住みやすい未来を確保するためには、気候変動の緩和と適応策が緊急に必要であると強調している。影響力があり、公平な措置を拡大することは、損失や損害をより小さくするだけでなく、ウェルビーイングやその他のシステムに大きな利益をもたらす。 EDITS メンバーはすでに、これらの科学的合意の発表を先駆けて、グローバル・サウスの特定の世界地域における一人当たりサービスの改善を通じてすべての人々のウェルビーイングを実現しながら、世界全体のエネルギー需要の削減をより迅速に進める必要性を強調してきた。

EDITS コミュニティは、モデル試算などの長期的なタスクを推進すると同時に、選択された重要なトピックをファストトラック（FT）ストリームとしてスピーディーに進めてきた。 EDITS が他の研究者や実装者ともっと連携する時期が来ている。「High-with-Low」シナリオは、EDITS 内の調査と活動の基礎として使用される。 これは、サービスエネルギー需要シナリオを複数の最終用途タイプにダウンスケールする DETRAS モデル（EDITS シェアポイントで利用可能）とリンクされている。 建物モデルや産業モデルなど、多くの検討が完了しており、運輸モデルの検討が進行中である。今年度、新たにウェルビーイングに関する作業グループを設け、需要側のさらなる作業に向けた概念的な基礎を開発した。全体像を完成させるために、多次元のウェルビーイングと実現可能性の枠組みが開発中である。

概要

EDITS 2023 年次総会は 11 月 6 日から 10 日までポルトガルのリスボンで開催した。年次総会は、EDITS イニシアチブ内での共同研究とモデリングの基本的な基盤である。 対面でのミーティングによって、深いディスカッションを組み合わせるためのフォーラムと、特定のワークフローを強化するための場所を提供した。 また、オンラインでの参加も可能とした。年次会議では、小規模な作業チームに集まり、科学論文、政策概要、伝達資料、さらにはデータベースなどの科学的成果物作成に向けて作業を進めた。

会合には、EDITS メンバーの約 40%と数人の外部科学者が参加した。会合参加者は、18 カ国（日本、米国、ドイツ、インド、ポルトガル、フランス、オーストリア、英国、イスラエル、オランダ、スイス、イタリア、ベルギー、ブラジル、韓国、中国、タイ、ハンガリー）から計 70 名であった。そのうち 58 名が直接参加し、12 名がオンラインで参加した。 出席者は、モデラー、社会科学者、経済学者、エンジニアなど、さまざまな分野の人々で構成された。 IPCC 第 6 次評価報告書執筆者も多数参加した。スムーズな議論と将来のコラボレーションの定義への注意を確保するために、参加は招待制に基づいて行った。参加者リストは後掲。

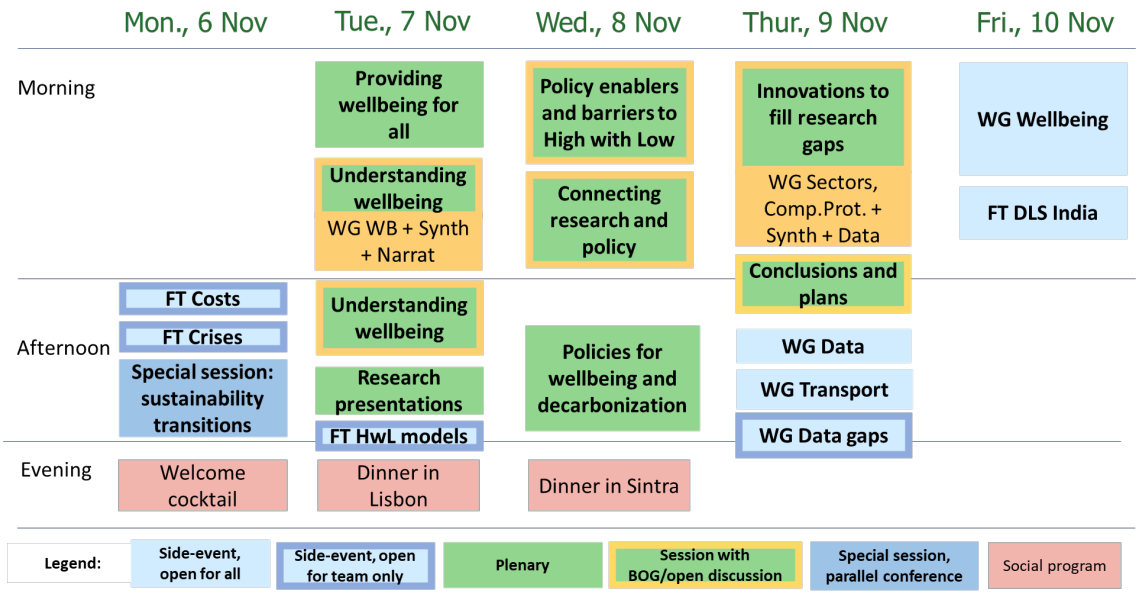
2023 年の EDITS 年次会議は、現在の重点分野に基づいて、以下の基礎となる 3 つの主要テーマが選択された。

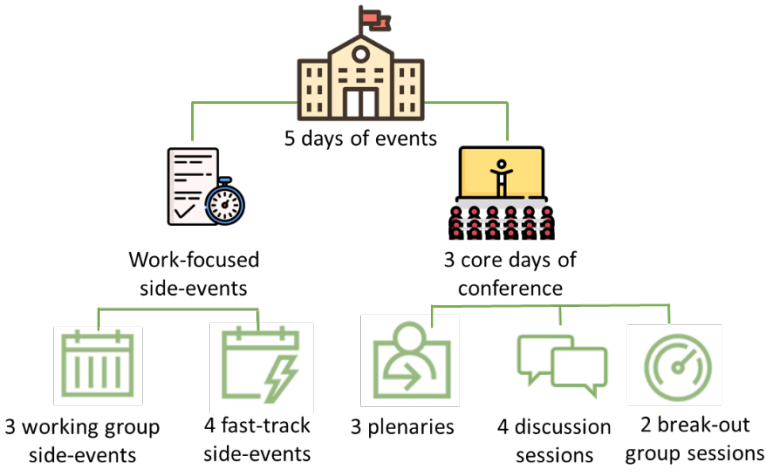
(1) ウェルビーイング
(2) 政策との連携
(3) 分野横断的な研究

この年次総会は、以下のようなセッション構成で実施した。

a) プレナリー: トピックの準備を整えるためにいくつかの基調講演が行われた (セッション 1、セッション 6、およびセッション 8)。
b) 以下のようなさまざまな作業グループによって構成されたディスカッション セッション:
   - セッション 2: ウェルビーイング WG、シンセシス WG、ナラティブ WG によるウェルビーイングとその対策に関するディスカッション
   - セッション 4: プロトコル WG とデータ WG による政策実現要因と障壁に関するディスカッション
   - セッション 5: プロトコル WG とナラティブ WG による政策への連携に関するディスカッション
   - セッション 7: 分野別 WG、データ WG、およびプロトコル WG によって構成された分野横断的な研究とモデリングに関するディスカッション。
c) 小規模なグループにより、より深く、より個人的なディスカッションが可能になった。
   - セッション 2: 特別なグループによるウェルビーイングのさまざまな側面についての議論
   - セッション 3: EDITS コミュニティが関連するアイデア、研究、結果を紹介する場を提供した。このセッションでは、小規模な内部グループが選択された専用トピックに取り組み、EDITS メンバーが EDITS の一部または外部として実施し、コミュニティにとって興味深いと思われる研究を発表することにつながるアイデアを募集した。
d) EDITS コミュニティは、並行して開催されるカンファレンス「持続可能性の移行」に招待され、低炭素ビジネス ソリューションのケーススタディについての洞察が得られた。

以下の通りに 5 日間、7 つのサイドイベントと 9 つのセッションで構成された。





上図記載のように、EDITS2023 年度の年次会議の中核プログラムに加えて、ワーキンググループやファストトラック（FT）に関連する会議もサイドイベントとして開催された。

- 特定の作業グループは、データ WG、トランスポート WG、ウェルビーイング WG の場合のように、複数年にわたるプログラムを進めるために専用の会議を実施した。
- ファストトラックストリームは実践的な会議を企画し、提出された論文（FT:High-with-Low モデリング、FT:DLS India、FT:Energy Security）の独自性について議論した。 他のファストトラックストリームは、セッションを使用して書き込みとデータ収集（FT:コストと機会、FT:危機、FT:データのギャップ）を進めた。

中核プログラムの構成及び会議内容は以下の通り。

会議内容

セッション

Session	Contents
1	Providing wellbeing for all
2	Understanding wellbeing
2a	Conceptual review and assessing wellbeing
2b	Provisioning systems of wellbeing
3	Complementary research and fast-track ideas - Research presentations
4	Policy enablers and barriers to High with Low
5	Connecting research and policy
6	Policies for wellbeing and decarbonization
7	Innovations to fill research gaps
7a	Gaps in demand sector modelling
7b	Moving ahead with modelling
8	Pathways for EDITS to improve wellbeing focus
9	Conclusions and plans

1. 開会

年次会議は、共同主催者である地球環境産業技術研究機構（RITE）の秋元圭吾氏とオーストリアの国際応用システム分析研究所（IIASA）の Bas van Ruijven 氏が開会の挨拶を行い、EDITS の戦略的目標を次のように要約した。

- 人間の幸福を測定するためのより良い指標
- デジタル経済の気候に与える影響評価
- シナリオモデリング
- システム相互作用の動的モデリング

また、開催地であるポルトガル、リスボン大学研究所（ISCTE）の Nuno Bento 氏は、参加者を歓迎し、また、エネルギー貧困などの多くの社会問題をかかえるポルトガルのような国において、需要側の行動によって問題を軽減できる可能性を紹介した。

主な議論内容

- ウェルビーイングとその提供システムの理解、説明、モデル化
- EDITS 外で、しかし EDITS に関連する需要関連の研究の発表
- ファストトラック（FT）につながる可能性のある EDITS に関する新しいアイデアの提案

2. セッション

セッション 1: すべてにウェルビーイングを提供する

EDITS 内および EDITS と並行して行われた最近の研究に焦点を当て、ウェルビーイングと低エネルギーおよび将来の資材需要の関係における概念的基礎について議論した。

- 移行とウェルビーイング
- グローバル・サウスにおけるウェルビーイングとは何か、そしてそれを達成する方法
- IPCC AR6 シナリオの多次元ウェルビーイング指標
- スイスでの充足(sufficiency)、ウェルビーイング、移行に関するシステムの視点
- 認識された生活の質に対する低炭素シナリオの影響を調べる：オランダでのパイロット研究

セッション 2: ウェルビーイングについて理解する

ウェルビーイング WG とシンセシス WG によって構成された。気候変動と実証されていない技術や高価な技術への依存を緩和しながら、エネルギーシステムの出力としてのウェルビーイングについて議論した。いくつかの導入プレゼンテーションの後、参加者は 以下の 2 つの関連する具体的なトピックについて議論を行った。

(1) 概念のレビューとウェルビーイングの評価

- EDITS が引き寄せる最も関連性の高いフレームの概念は何か?
- どの方法（モデリングと非モデリング）が最も有用で、EDITS アクティビティに必要か?
- ウェルビーイングをシナリオの中心要素にするための手順は何か?
- 状況に応じたウェルビーイングの意味は何か: グローバルノース/グローバルサウス、田舎/都会、若者/高齢者、性別の違いなど? モデル内の異質性をどのように表現できるか?
- シナリオは常にウェルビーイングに焦点を当てるべきか? また、幸福はどのように評価できるか? SSP を超えるにはどうすればよいか?
- モデルで使用できる（定量的な）パラメータを提案できるか？

(2) ウェルビーイングのための対策システム

- 低炭素ソリューションを使用してすべての人にウェルビーイングを提供するにはどうすればよいか?
- すべての人にウェルビーイングを提供するための、関連する技術的、社会的、特に制度的、インフラ的要件は何か？
- より包括性と正義を確保するにはどうすればよいか？
- グローバル・ノースとグローバル・サウスの両方における充足感の役割は何か? リソースへの影響は何か?

セッション 3: 補完的研究と迅速なアイデア

発表者は、EDITS では扱っていないが、密接に関連する需要側の研究のアイデアを紹介した。そのあと、以下のテーマで自由討論を行った。

(1) どのような対応方法：成功要因と趨勢

- エネルギー需要が低い社会は、脱炭素化への道筋における鉱物への懸念をどの程度軽減できるか?
- 日本のエネルギーイノベーション金融と市場および政策メカニズムの影響
- 国家充足シナリオを詳しく説明する提案
- デジタル コンバージェンス

(2) HwL の未来におけるモビリティと輸送

- GHG 排出量を最小限に抑えながら、世界中のモビリティインフラストラクチャへのユニバーサルアクセス
- ブラジルの貨物輸送におけるディーゼル節約に対する道路品質の影響
- まともなモビリティのニーズとは何か?
- 需要側の政策シナリオ：ドイツの旅客輸送のケース

(3) HwL にフォーカス

- 低エネルギーの未来に対する公的支援と関与
- 心理学の理論と発見を使用して、ライフスタイルの変化をより現実的にモデル化するにはどうすればよいか?
- エネルギー需要を削減するための手段を人口内で差別化する：スイスの住居の事例
- スケールのバランスを取る：インドのエネルギー、排出量、生活の質

セッション 4: HwL の実現要因と障壁となる政策

政策と決定は、エネルギーサービスが提供および消費される環境を変革する。 政策枠組みは、対策の有効性、コスト、成功に大きく貢献する。 需要側と連携する既存および潜在的な政策を批判的に評価するための以下の発表によりプラットフォームが提供され、パネルディスカッションが行われた。

- ウェルビーイングのためのイノベーション
- 十分性政策はどのようにして成功するのか – 現在の研究からのいくつかの論文
- HwL の実現要因としてのデジタル化の政策
- ファイナンスの観点からの考察

セッション 5: 研究と政策の接続

政策決定に対して科学が持つ責任と機会に焦点を当てた。 需要側の政策によってもたらされる機会をとらえ、これらをうまく実施するための可能性と困難について議論した。 これらの政策を知らせるためにど

のような調査、データ、指標が必要かを検討した。 緊急性のメッセージや解決策のアイデアが関連政策につながるのはなぜなのか、なぜそうでないのかが問われた。以下の発表後、パネルディスカッションが行われた。

- 政策を通じて低エネルギーで高い福祉を実現するために IPCC が提供できるもの
- 需要側の角度から見たエネルギー安全保障
- コストデータと政策のギャップを埋めてデマンドサイドのソリューションを強化
- 需要側排出削減と関連政策・措置

セッション 6: ウェルビーイングと脱炭素化のための政策

このセッションは、シントラのバレンサス宮殿で開催された。

まず、シントラ副市長からの歓迎とオープニング: 「産業政策と気候と持続可能性の目標における新しい傾向」のスピーチの後、応用デジタル技術大学イシュテ・シントラ校の学部長が「経済を回復させカーボンニュートラルを実現するためのポルトガルの戦略」を紹介した。特別名誉研究員、国際応用システム分析研究所 (IIASA)、オーストリアの EDITS 創設者 Arnulf Grübler 氏が、「エネルギー需要対策の政策上の利点: EDITS から学んだ教訓」を発表した。地球環境産業技術研究機構 (RITE) 理事長、山地 憲治氏が「低エネルギー需要の将来に向けた日本の政策」を紹介した後、世界のウェルビーイングを改善し、複数の目標 (経済、気候、ウェルビーイングなど) を達成するためエネルギー需要の解決策と産業政策がどのように相互作用するかを検証し、実装の選択肢と課題についてパネルディスカッションと公開ディスカッションが行われた。

セッション 7: 研究のギャップを埋めるための EDITS イノベーション

セクター、データ、プロトコル、シンセシスなどの複数のワーキング グループによって構成され、セクター間の領域を調査した。 これは、既製の枠を超えて EDITS 内およびその周辺の知識を深めようというコミュニティからの呼びかけに基づいて構築された。これらの分野の概念的枠組みとモデル化における重要なギャップを正確に指摘するために、上記ワーキンググループですでに完了した作業をさらに発展させていき、続いて、補完プロトコルから得られた最初の結果と教訓を検討し、ウェルビーイングやその他の需要側の人間の利益をより良くする機会について議論した。

(1) 需要セクターのモデリングにおけるギャップ

- 建築セクター代表の現在の慣行における主なギャップ
- 運輸部門の代表に関する現在の慣行における主なギャップ
- 産業部門の代表に関する現在の慣行における主なギャップ
- 討論者の反応

(2) モデリングを前進させる

- 第一弾のシナリオ分析の集約から得た教訓と SSP アップデートの関連性

- 討論者の反応

セッション 8: ウェルビーイングの焦点を改善するための EDITS の道筋

最後のセッションでは、IIASA の Benigna Boza-Kiss 氏が司会を務め、EDITS の成果を評価し、研究と政策に最大の影響を与えることができる最も効果的な介入ポイントを特定することが重要であると述べた。 昨年の成功を強調し、今後の方向性についての推奨事項や要望を表明する機会を提供した。

コメントと提案の抜粋は次のとおり。

- EDITS はよりアクション指向に移行しており、物事は前進している。 需要側の対策について外部に向けて発信し、さらなるコミュニケーションを活発化させる時期が来ている。 重要なセールスポイントとして COP27 でインドは、環境のためにライフスタイルを変える「ライフミッション」を打ち出した。
- 概念的なアイデアを具体的なモデリングに結び付けることが重要である。 モデルにおけるシナリオのナラティブがより現実的に解釈できるよう考慮することにより、政策立案者に受け入れられるのに役立つ。 日本と韓国では、十分性の考えが社会的に受け入れられている。 昨年の会議と比較して、十分性についての理解が大幅に向上した。
- この会議は、歴史的なテクノロジーの採用から、歴史的な行動の採用への移行に対する人々の関心について重要な洞察を与えた。社会革新を含む態度や行動によってどのように変化するかを示すのは興味深い。
- 数年が経ち、EDITS は比較的確立されたコミュニティになり、新たな関心が集まった。 コミュニティは非常にグローバル・ノース指向であり、ヨーロッパ的でが、 広くコミュニケーションをとる必要がある。
- 世界の他の国々に手を差し伸べ、対話するためには、ウェルビーイングを数値化し、経済コミュニティとつながることができる必要がある。 HwL は世界が直面している多くの問題の解決策のように思えるが、学問志向になりすぎることにも注意し、より多くの現地の事例研究が必要。政策にするには、明確なコミュニケーション目標が必要であり、政治経済的要因に対処する方法が必要で、「需要と供給」を超えた物語の枠組みが必要。多国間での公平性が主な利点/セールスポイントである。
- 会議に関しては、対面での議論が役に立った。 ウェルビーイングの概念的な枠組みについて、十分性を好む人は、この部屋の外ではあまり受け入れられないかもしれない。SF ベイエリアにおけるゾーニング改革の例は、十分性と結びついているものの、別の方法で枠組み化されている。 これらのアクセス可能かつ実行可能なアクションをどのように特定すればよいか? 私たちはウェルビーイングの理解から優れた洞察を収集できたが、さまざまな状況や国でどのように定義するかについてはまだ疑問がある。 外部の関係者特に政策立案者とつながる方法、他にも住宅危機、エネルギーアクセスなど競合する問題がある。
- コミュニティは、ナラティブのコミュニケーションに関するワーキンググループを求めている。

- ウェルビーイング指標に成果を結び付けるためにやるべきことはまだたくさんあり、それが焦点となる可能性がある。 粒度や異質性についてさらに深く掘り下げたほうがよいかもしれない。

3. 閉会

IIASA の Bas van Ruijven 氏、RITE の山地 憲治氏、リスボン大学研究所の Nuno Bento 氏による閉会の挨拶により、3 日間のプログラムは閉会となった。

その他、サイドイベントや会議詳細は、IIASA の報告内容を参照。

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	Research Institute of Innovative Technology for the Earth (RITE)	Kenji Yamaji	
2			Keigo Akimoto	Ch.17 LA*
3			Ayami Hayashi	
4			Atsuko Fushimi	
5			Jubair Sieed	
6			Dahyun Kang	
7		University of Tokyo, Institute for Future Initiatives (UTokyo IFI)	Masahiro Sugiyama	Ch. 12 LA
8			Tao Cao	
9			Hiroyoshi Iwata	
10		Osaka University; Urban Energy System Lab.	Yoshiyuki Shimoda	
11			Keita Shono	
12		United Nations University (UN Uni)	Joni Jupestra	Ch.17 LA
13	Austria	International Institute for Applied Systems Analysis (IIASA)	Arnulf Grübler	Ch.5 LA
14			Bas van Ruijven	
15			Benigna Boza-Kiss	
16			Paul Kishimoto	
17			Alessio Mastrucci	
18			Leila Niamir	Ch.5 CS*
19			Shonali Pachauri	Ch.2, LA*
20			Caroline Zimm	
21		Vienna University of Technology	Nebojsa Nakicenovic	

	国	組織名	参加者名	IPCC 関係者
22		Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna (BOKU/SEC)	Dominik Wiedenhofer	
23			Jan Streeck	
24	France	EDHEC Business School	Gianfranco Gianfrate	
25		International Transport Forum (ITF/OECD)	Luis Martinez	
26		University of Lausanne/OpenExp	Yamina Saheb	Ch.9 LA*
27		Réseau de Transport d'Electricité (RTE)	Bianka Shoai-Tehrani	
28			Audrey Berry	
29	UK	Imperial College London (ICI)	Simon De Stercke	
30		University of Oxford	Charlie Wilson	Ch.5 CA
31			Poornima Kumar	
32		University of Plymouth	Souran Chatterjee	
33		University of Leeds	Jonathan Norman	
34	Italy	Euro Mediterranean Center on Climate Change (CMCC)	Massimo Tavoni	Ch. 3 LA
35			Elena Verdolini	Ch.16 LA*
36			Leticia Magalar	
37			Yannik Stuka	
38	Germany	Technical University Berlin	Marlin Arnz	
39		Oeko-Institut	Frauke Wiese	
40			Carina Zell-Ziegler	
41		Wuppertal Institute for Climate, Environment and Energy, Energy Policy Research Unit	Johannes Thema	
42	Belgium	Ghent University	Maria Fernanda Godoy Leon	
43	Portugal	University Institute of Lisbon (ISCTE-IUL)	Nuno Bento	
44			Tristão de Quiroga	

	国	組織名	参加者名	IPCC 関係者
45			Maria João Machado	
46			Dalia Soto	
47			Tiago Domingos	
48	Hungary	Central European University (CEU)	Diana Urge-Vorsatz	ViceChair, Ch.8 RE*
49	Netherlands	Universiteit Utrecht (UU)	Oreane Edelenbosch	
50		University of Groningen	Linda Steg	Ch.6 LA*
51			Anne van Valkengoed	
52	Switzerland	EPFL Laboratory of Environmental and Urban Economics (EPFL)	Sascha Nick	
53		University of Lausanne	Vivien Fisch-Romito	
54	India	Center for Study of Science, Technology and Policy (CSTEP)	Kaveri Ashok	
55			Aparna Sundaresan	
56	Thailand	Asian Institute of Technology (AIT)	Joyashree Roy	Ch.5 CLA*
57	South Korea	Yonsei University/Korea International Economic Association	Tae Yong Jung	Ch.15 CLA*
58			Jongwoo Moon	
59			Yong-Gun Kim	Ch.2 LA
60	China	Tsinghua University	Xunmin Ou	
61	USA	Lawrence Berkeley National Laboratory (LBNL) - Building Technology and Urban Systems Division/Net Zero World Action Center (NZW)	Nan Zhou	Ch.4 LA
62			Jingjing Zhang	

	国	組織名	参加者名	IPCC 関係者
63		University of California, Santa Barbara (UCSB)	Eric Masanet	Ch.3 CA, Ch.5 LA, Ch.16 CA
64		Oak Ridge National Laboratory (ORNL)	David McCollum	Ch.3 CA, Ch.6 CA, TSU*
65		Wisconsin Energy Institute/ University of Wisconsin	Gregory Nemet	Ch.2 LA
66		Yale School of the Environment	Karthik Akkiraju	
67			Narasimha Rao	
68	Brazil	Economia da Energia do Programa de Planejamento Energético da COPPE/UFRJ	Roberto Schaeffer	Ch.3 CLA*
69			Ana Jacomit	
70	Israel		Tzruya Calvão Chebach	

* 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	1.Modeling and implementing sufficiency to achieve high well-being with low energy demand [*Abstract only]	Lawrence Berkeley National Laboratory (LBNL)	Jingjing Zhang, Nina Khanna, Michelle-Johnson Wang, Nan Zhou
	2.Closing the information gap for implementing ambitious mitigation: what works at what costs [*Abstract only]		Jingjing Zhang, Michelle Johnson Wang, Hon Leung Curtis Wong, Nan Zhou In collaboration with Joyashree Roy, Shreya Some, Huzaifa Butt and others including Eric Masanet, Leila Niamir, Luis Martinez, Souran Chatterjee, BOZA-KISS Benigna
③	A data mapping exercise to identify key data gaps in the description of Low Energy Demand Pathways [*Abstract only]	Utrecht University	Oreane Edelenbosch
④	Implications of reducing diesel demand in Brazil's transport sector for meeting the country's climate goals [*Abstract only]	The Universidade Federal do Rio de Janeiro, (UFRJ), COPPETEC	Alberto Santos, Pedro Maia, Rodrigo Jacob, Huang Wei, Camila Callegari, Ana Carolina Oliveira Fiorini, Roberto Schaeffer, Alexandre Szklo
⑤	Energy Demand in South and South-East Asian countries: Decoupling status, Modelling Approaches and Socio-technical & Cultural Transitions	Asian Institute of Technology (AIT)	Joyashree Roy
⑥	Carbon Footprint and Economic Analysis of China's Ammonia Energy	Tsinghua University	OU, Xunmin; YANG, Yifang; REN, Lei; LIU, Jianzhe; CHEN, Zeyu
⑦	1.The potential of digital convergence and sharing of consumer goods to improve living conditions and reduce emissions	Iscte – University Institute of Lisbon	Nuno Bento
	1a.Supplementary Information		
	2.Leverage demand-side policies for energy security		Nuno Bento, Arnulf Grubler, Benigna Boza-Kiss, Simon De Stercke, Volker Krey, David McCollum, Caroline Zimm, Tiago Alves
	2a.Supplementary Materials for Greater leverage for energy security with demand-side policies		Nuno Bento, Arnulf Grubler, Benigna Boza-Kiss, Simon De Stercke, Volker Krey, David McCollum, Caroline Zimm, Tiago Alves

	タイトル	研究所・大学	著者
⑧	1.Balancing Energy Transition: Assessing Decent Living Standards and Future Energy Demand in the Global South [*Abstract only]	University of Plymouth	Souran Chatterjee, Alessio Mastrucci, Leila Niamir, Kaveri Ashok, Ashok Sreenivas, Srihari Dukkipati, Vassilis Daioglou, Oreane Edelenbosch, Setu Pelz, Benigna Boza-Kiss, Poornima Kumar, Diána Ürge-Vorsatz
	2.High well-being with low energy consumption: scenarios for residential India [*Abstract only]		Alessio Mastrucci, Souran Chatterjee, Kaveri Ashok, Vassilis Daioglou, Srihari Dukkipati, Oreane Edelenbosch, Sarah Khan, Poornima Kumar, Ashok Sreenivas, Diana Ürge-Vorsatz, Victhalia Zapata, Shonali Pachauri
⑨	Pathways to Achieve Net-Zero and Energy Independence Transition in the EU Building Sector [*Abstract only]	DBH InnoHub (Central European University (CEU))	Diana Ürge-Vorsatz, Souran Chatterjee
⑩	Analyzing Low Energy Demand Scenarios: CGE and Index Decomposition with Climate Change Impact Assessment	Korea International Economic Association (KIEA),(Yonsei University)	Tae Yong Jung
⑪	A Final Comparison of the EMF 37 and EDITS Projects: Objectives, Execution and Results	Stanford University	John P. Weyant
⑫	Model complementarity exercise on demand-side innovations for climate change mitigation [*Abstract only]	東京大学 未来ビジョン研究センター	東京大学 未来ビジョン研究センター
⑬	Evidence synthesis of indirect impacts of digitalisation on energy and emissions [*Abstract only]	Oxford University	Charlie Wilson, Maureen Agnew, Pippa Amanta, Yee Van Fan, Poornima Kumar, Marcel Seger

	タイトル	研究所・大学	著者
⑭	1.Review of industry modelling Low Energy and Material Demand Scenarios Findings: Material stocks for Decent Living Standards around the world	University of Natural Resources & Life Sciences, Vienna (BOKU)	Dominik Wiedenhofer and Jan Streeck
⑭&⑮	Material Cycles, Industry and Service Provisioning: A Review of Low Energy and Material Demand Modelling and Scenarios a.Supplementary Information	BOKU and CMCC	Dominik Wiedenhofer, Jan Streeck, Frauke Wiese, Elena Verdolini, Alessio Mastrucci, Yiyi Ju, Benigna Boza-Kiss, Jihoon Min, Jonathan Norman, Hanspeter Wieland, Nuno Bento, María Fernanda Godoy León, Leticia Magalar, Andreas Mayer, Simone Gingrich, Ayami Hayashi, Joni Jupesta, Gamze Ünlü, Leila Niamir, Tao Cao, Marianne Zanon-Zotin, Barbara Plank,Eric Masanet, Volker Krey, Keigo Akimoto, Arnulf Grubler, Bas van Ruijven, Stefan Pauliuk
⑮	2.Electricity Consumption in the Italian Retail Electricity Market	Euro-Mediterranean Centre for Climate Change (CMCC)	Matteo Muntoni
	3.Multi-dimensional wellbeing of IAM scenarios: an assessment of the illustrative mitigation pathways of the IPCC 6th assessment report		Elina Brutschin, Shonali Pachauri, Yannik Stuka and Massimo Tavoni
⑯	1.Modelling Low Energy Demand Futures for Transport: Current State and Research Needs [*Abstract only]	ITF-OECD	Hugh Thomas, Luis M. Martinez, Paul Natsuo Kishimoto, Felix Creutzig, Yamina Saheb
	2.Global trajectory for urban passenger transport decarbonisation: a policy-based modelling approach [*Abstract only]		Mallory Trouvé, Nicholas Caros and Luis Martinez
	3. Modelling intercity and long-distance passenger travel decarbonisation pathways [*Abstract only]		Andrea Papu Carrone, Luis Martinez
	4. Modelling global freight decarbonisation pathways [*Abstract only]		Luis Martinez and John P Pritchard
	5. Rethinking Transport Sustainability: Insights from the ITF PASTA Global Fleet Model [*Abstract only]		Matteo Craglia and Luis Martinez
	6. Shared mobility's role in sustainable mobility: past, present, and future [*Abstract only]		Luis M. Martinez, John P. Pritchard, Philippe Crist
	7.Summary of activities within EDITS network		ITF-OECD

	タイトル	研究所・大学	著者
⑰	EDITS WG4 Wellbeing Report	EPFL	EPFL
⑱	Evaluation of the impact of low carbon lifestyles on quality of life	University of Groningen	Anne M. van Valkengoed & Linda Steg
⑲	2023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	大阪大学 下田研究室
⑳	1.Social innovation enablers to unlock a low energy demand future	University of Wisconsin	Leila Niamir, Elena Verdolini, and Gregory F. Nemet
	2.The 'High-with-Low' Scenario Narrative: Key Themes, Cross-Cutting Linkages, and Implications for Modelling		Charlie Wilson, Arnulf Grubler, Gregory Nemet, Shonali Pachauri, Stefan Pauliuk, Dominik Wiedenhofer
	3. Technological innovation enables low cost climate change mitigation		Felix Creutzig, Jérôme Hilaire, Gregory Nemet, Finn Müller-Hansen, Jan C. Minx
㉑	Annual Report - Energy Demand changes Induced by Technological and Social innovations (EDITS)	International Institute for Applied Systems Analysis (IIASA)	IIASA
㉒	Review and compilation of best available data and modeling approaches for assessing the infrastructure energy use of data centers and artificial intelligence in energy demand models	University of California, Santa Barbara (UCSB)	Eric Masanet
㉓	Policy brief: Harnessing the sufficiency potential in global climate mitigation pathways of IPCC AR6 SPM with a temperature target of 1.5℃ by the end of the centrury [*Abstract only]	OpenExp	Yamina Saheb and Maria Messaoud Nacer

*ジャーナル掲載前の論文のため、abstractのみ公開

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

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。他方、2023 年 12 月に開催された COP28 のグローバル・ストックテイク（GST）の決定文書では、「最新の NDCs が完全に実施された場合には 2.1～2.8℃の範囲の上昇」の見通しとなるされた。また、世界の温室効果ガス排出量は過去最大を更新しつづけており、主要先進国の排出量のトレンドも 2030 年 NDCs 達成に向けて順調にはいっておらず、NDCs の完全実施も容易ならざる状況である。このように、パリ協定長期目標の well below 2℃目標や 1.5℃目標の達成は難しさを増している。

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、2023 年 5 月に「脱炭素成長型経済構造への円滑な移行の推進に関する法律」（通称 GX 推進法）が成立した。

パリ協定長期目標達成の厳しさが増す中、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。

1.1　需要対策の政策動向

本 EDITS プロジェクトは、2019 年 6 月の G20 軽井沢アクションプランでの決議：「我々は、将来のエネルギー需給のより良い理解に関する定量分析の重要性、並びに、デジタル化、人工知能（AI）、インターネットオブシングス（IoT）及びシェアリングエコノミーによって牽引される需給両面のイノベーションの役割を認識する。我々は、世界の科学コミュニティ及び国際機関・枠組によってなされる、エネルギー・気候モデルのための経済全般にわたる全範囲シナリオのさらなる洗練及び開発のための努力を支持する」
が契機となって、実施されている。

2023 年 4 月に開催された G7 札幌気候・エネルギー・環境大臣会合の成果文書でも多くの本研究調査内容に関連した決議が掲載された。以下は、関連深い記述の例である。

G7 札幌気候・エネルギー・環境大臣会合コミュニケより抜粋

31 項. 循環性及び資源効率性の強化を通じた三つの地球規模の危機への対処: 経済成長と環境劣化や一次資源の利用とのデカップリングの重要性を強調し、科学的データと知見に導かれたバリューチェーン全体における資源効率性及び循環性の向上が、一次資源の利用を減じ、三つの地球規模の危機に取り組む我々の努力を支援することを強調する。我々は、ライフサイクル・アプローチを踏まえた製品設計の強化、ライフサイクル評価、適切な場合には拡大生産者責任のスキーム等を含み得る様々なアプローチを通じ、バリューチェーンにおける循環性を高めるための幅広い政策措置と民間セクターとの協力を強化することによって我々の経済がより循環性及び資源効率性の高いものとなるよう努力する。我々は、野心的な気候や環境目標の実現のために資源効率性や循環経済の可能性を活用するべく協力する。

51 項. バリューチェーン全体での排出削減を実現する視点: 我々は、気温上昇を 1.5℃に抑えることを射程に入れ続けるために、様々な主体による、即時、迅速かつ持続的に自らの及びバリューチェーン全体における GHG 排出を削減するための継続的な努力の重要性を強調し、優先する。我々は、民間セクター含めポジティブな気候行動を更に奨励し、事業者が、自らの及びバリューチェーン全体における GHG 排出のネット・ゼロへの道にコミットすることを奨励する。我々は、特に民間のネット・ゼロ・プレッジの信頼性を含め、非国家主体のネット・ゼロ排出コミットメントに関する国連ハイレベル専門家グループの作業を認識する。また、ある系における脱炭素ソリューション提供による、ある事業者による他の事業者の排出削減への貢献、すなわち、「削減貢献量」を認識することも価値がある(参照: 附属文書「産業の脱炭素化アジェンダに関する結論」パート B)。我々は、削減貢献量に関する信頼できるメカニズムが、ソリューションの展開を加速するための資金を動員し得ることに注目し、持続可能な開発のための経済人会議(World Business Council For Sustainable Development)が、3 月に発表した削減貢献量に関するガイダンスの初版を、削減貢献量の主張に関する議論への民間セクターの貢献として注目する。G7 産業脱炭素化アジェンダ(IDA)に関する結論で示された原則に沿って、消費者及び企業、投資家に効率的な排出削減を加速化するための力を与え、また、不適切に用いられるリスクを低減するため、我々は、様々な主体による環境パフォーマンスに関する主張が、信頼性、比較可能性、検証可能性を有するべきであることを強調する。

53 項. 需要サイドの行動: IPCC の第6次評価報告書(AR6)統合報告書の見解知見によれば、需要サイドの対策と新たな最終用途のサービスの対策提供により、最終用途分野部門における世界の GHG 排出量をベースラインシナリオと比較して 2050 年までに 40～70%削減することができ、また、政策、インフラ、及び技術に支えられた社会文化的な選択肢、行動やライフスタイルの変化は、最終ユーザーが複数の相互利益を伴う低排出量集約型が低い消費への移行を支援することができる。インフラの利用、設計、建築物の利用、最終使用技術の採用、及び消費者の選好などの需要サイドの変化を促進するためには、産業界やステークホルダーへの適切なガイダンス、及びより良い排出関連情報、適切な規制及び価格シグナルの

提供を通じ、消費者の意識を高め、彼らの選択を支援することが重要である。我々は、デジタル化や消費者の選好に影響を与えるようなインセンティブの増加を含め、低炭素及びゼロ・エミッション製品やサービスの開発、及び省エネルギー達成を促進するための政策手段を拡充する。効果が高く、社会的に公正な施策を立案するためには、企業、地方自治体、社会団体、若者、及び市民と協力し、知識や経験を共有することが重要である。したがって、我々は「脱炭素で豊かな暮らし(ウェルビーイング)のためのG7プラットフォーム」を設立し、我々の気候目標に沿った持続可能な消費者の選好を奨励することに貢献するイノベーションのための官民パートナーシップの加速を目指す。我々は、低炭素及びゼロ・エミッション製品やサービス、及び需要サイドの政策に関する経験や優良事例を共有することで、他者を支援する。

63 項. 省エネルギー: 我々は、2050 年の温室効果ガスのネット・ゼロ排出に向けた世界的なエネルギー転換における重要な柱として、「第一の燃料」としての省エネルギーの役割を強調する。我々は、エネルギーの安全保障、アクセス及び低廉性を強化しながら、温室効果ガス排出の削減と環境への影響の緩和、経済成長の創出とエネルギー貧困の削減において、あらゆる部門における省エネルギーとエネルギーの節減の価値を強調する。我々は、情報キャンペーン、消費者の嗜好への影響と対応、需要最適化措置、エネルギー効率の高い機器とソリューションの促進を含む、現在のエネルギー危機への対応として我々が既に行った、成功した措置を基に、起こりうる反動効果にも対処しつつ、エネルギー消費を削減するための需要側の取組の必要性を認識する。我々は、IEA に対し、ベストプラクティスを特定し、共有し、推奨するため、現在のプレッシャーに反応して需要の削減対策が既にもたらした影響を評価することを求める。さらに、我々は、効果的かつ効率的な規制の枠組みの重要性を認識し、技術的及び非技術的な解決策の両方を促進するために公的及び民間資金を活用する必要性を認識する。我々は、政策、計画及び投資の決定において、省エネルギーとエネルギーの節減が正当に考慮されることを確保するために、「省エネルギーファースト」が我々の行動の推進原理として認識される必要性を強調する。また、自動車燃費規制、建築基準、最小エネルギー性能基準、エネルギー性能証明書、大規模需要家のエネルギー報告制度などの省エネルギー規制が、引き続き勢いを増していることに留意する。これらの施策は、電化、燃料転換、系統柔軟化、エネルギー需要情報のデジタル化、エネルギー・気候関連情報の開示を含む戦略的アプローチによるエネルギー需要の脱炭素化に向けた更なる取組を活用していく。我々は、需要側の脱炭素化目標に沿った省エネルギー規制の枠組みの進化に関する IEA の分析を歓迎し、省エネルギー政策の強化を支援するために、新興国の政府を含む各国政府とこの情報を共有する予定である。この取組において、IEA のネット・ゼロシナリオと整合性を持たせるためには、2030 年まで一次エネルギー原単位を世界的に年 4%改善させる必要があると IEA が予測していることに留意する。

2023 年 12 月の COP28 でのグローバル・ストックテイク（GST）成果文書でも、「気候変動への対応への取り組みにおいて、サーキュラー経済のアプローチを含み、持続可

能なライフスタイルと持続可能な消費と生産パターンへの移行重要性を認識し、この点での努力を推奨する。」とされた。

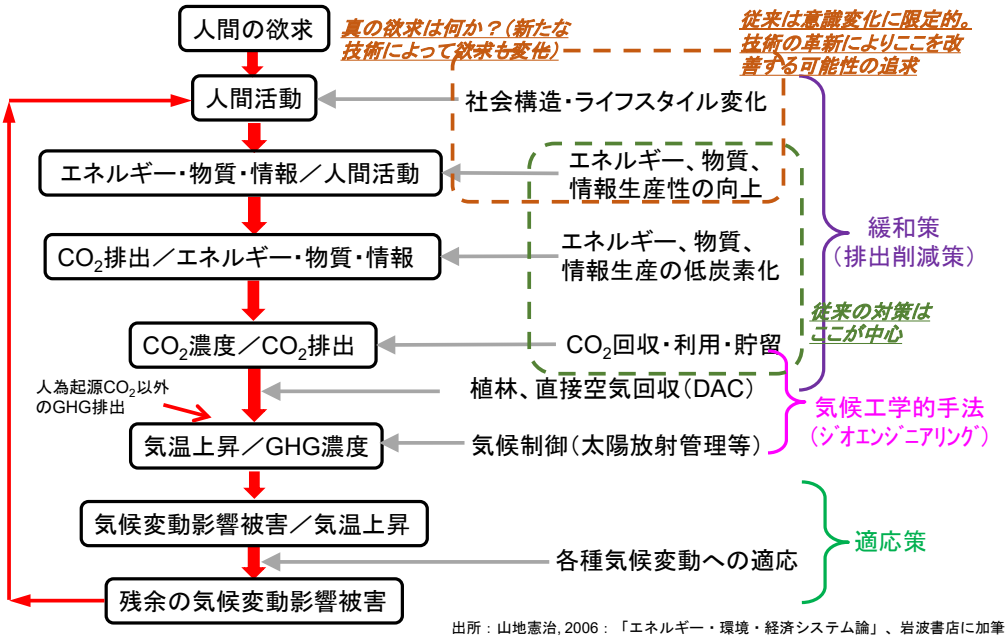
需要サイドの適切な取り組み強化は、困難さを増しているパリ協定長期目標の達成を呼び戻せる可能性があるとともに、SDGs の同時達成へのアプローチでもある。

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。今年度は、G7 札幌コミュニケでも言及されている、”Avoided emissions（削減貢献量）”の視点にも焦点を当てて分析を行った。

1.2 エネルギー需要側対策の既往分析

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。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 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 1-1 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 1-2、図 1-3 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。

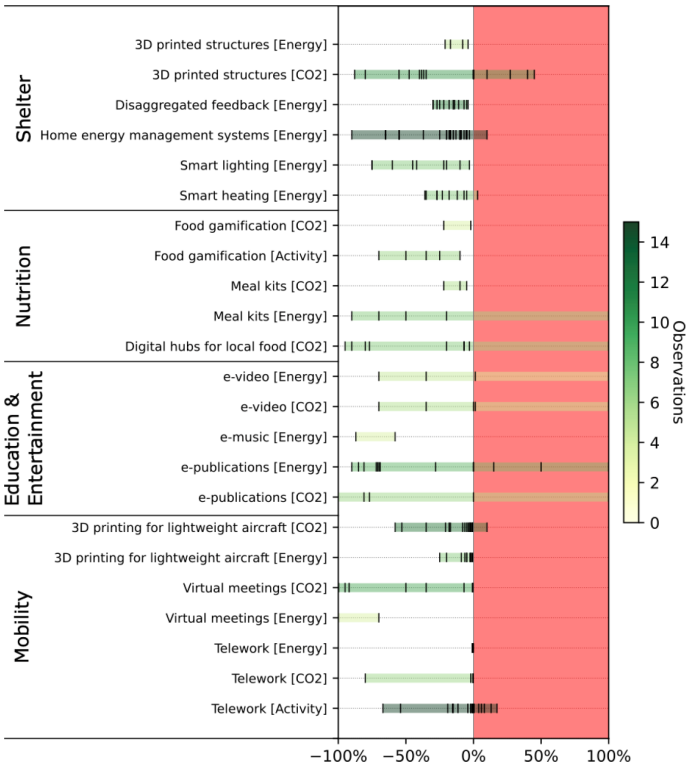


図 1-2 デジタル化によるエネルギー消費・CO_2 排出への影響

（出典：IPCC WG3 AR6[4]）

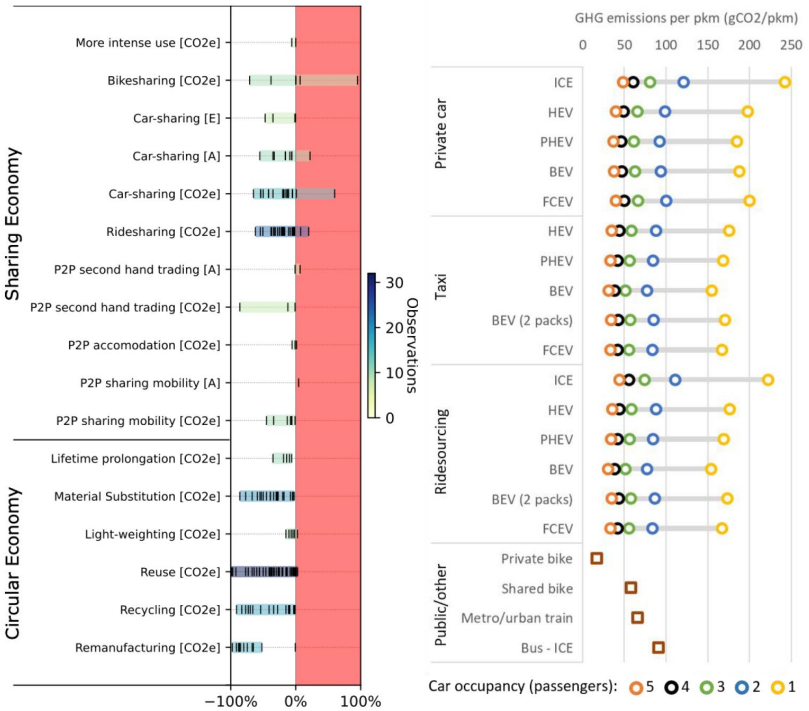


図 1-3 シェアリング・サーキュラーエコノミーによるエネルギー消費・CO_2 排出への影響

（出典：IPCC WG3 AR6[4]）

1.3　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。

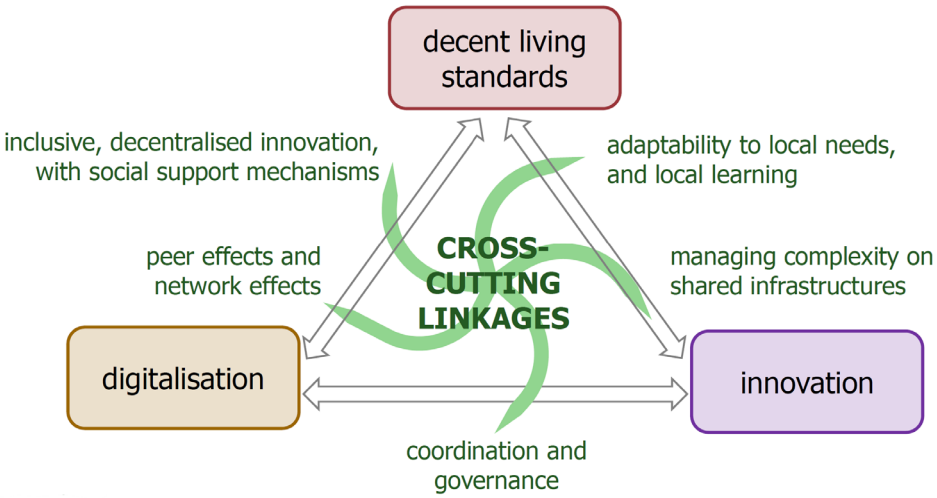


図 2-1　定性的シナリオ’High-with-Low’の想定ドライバー
（出典：EDITS WG3 Narratives group シナリオ [6]）

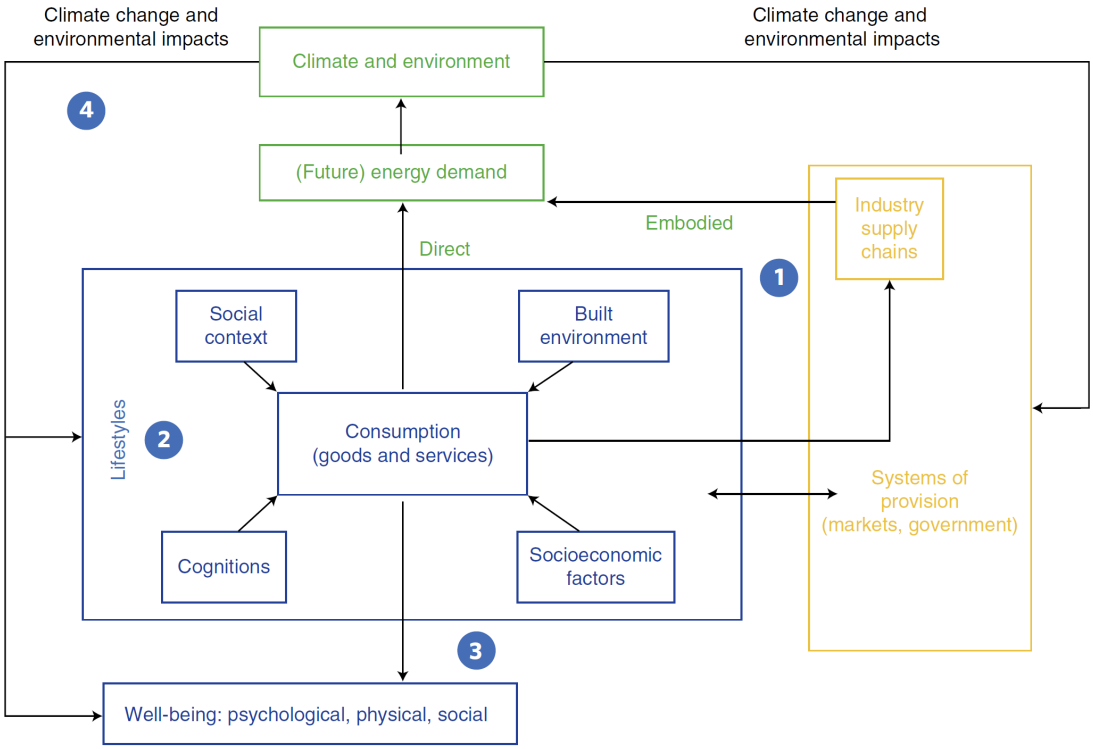


図 2-2 定性的シナリオ’High-with-Low’の要素間の関係

（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。他方、15DS シナリオでは、世界全体で CO_2 限界削減費用の均等化を想定した。

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		○	○	○	○	○	○	○	○
15DS-Std	15DS 1.5℃未満(MAC均等)	—	—	—	—	—	—	—	—
15DS-All_CE+FL+GR		○	○	○	○	○	○	○	○

注1) 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。

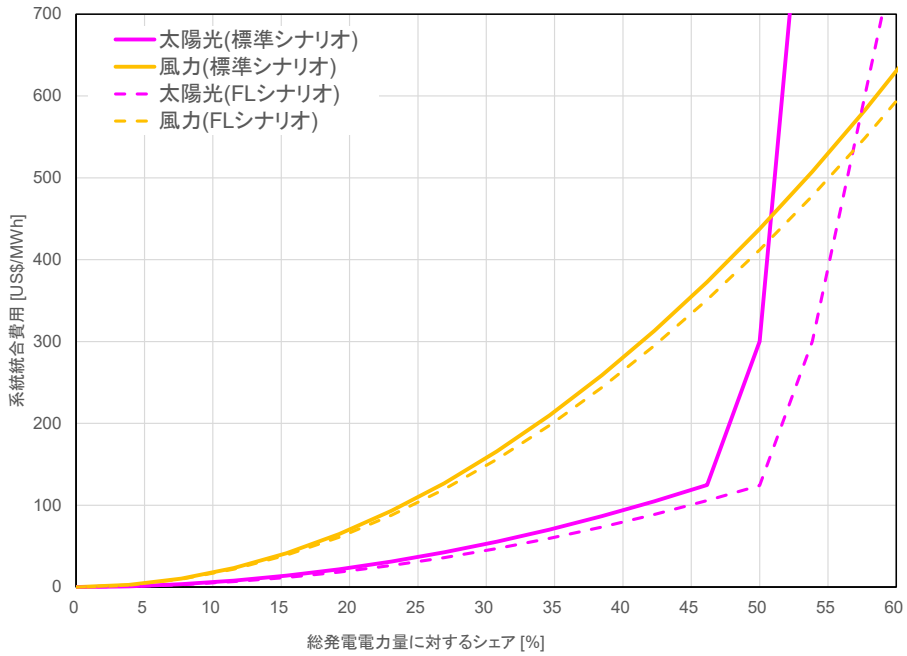


図 2-3 系統統合費用の想定（日本、2050 年、標準シナリオと FL シナリオ）

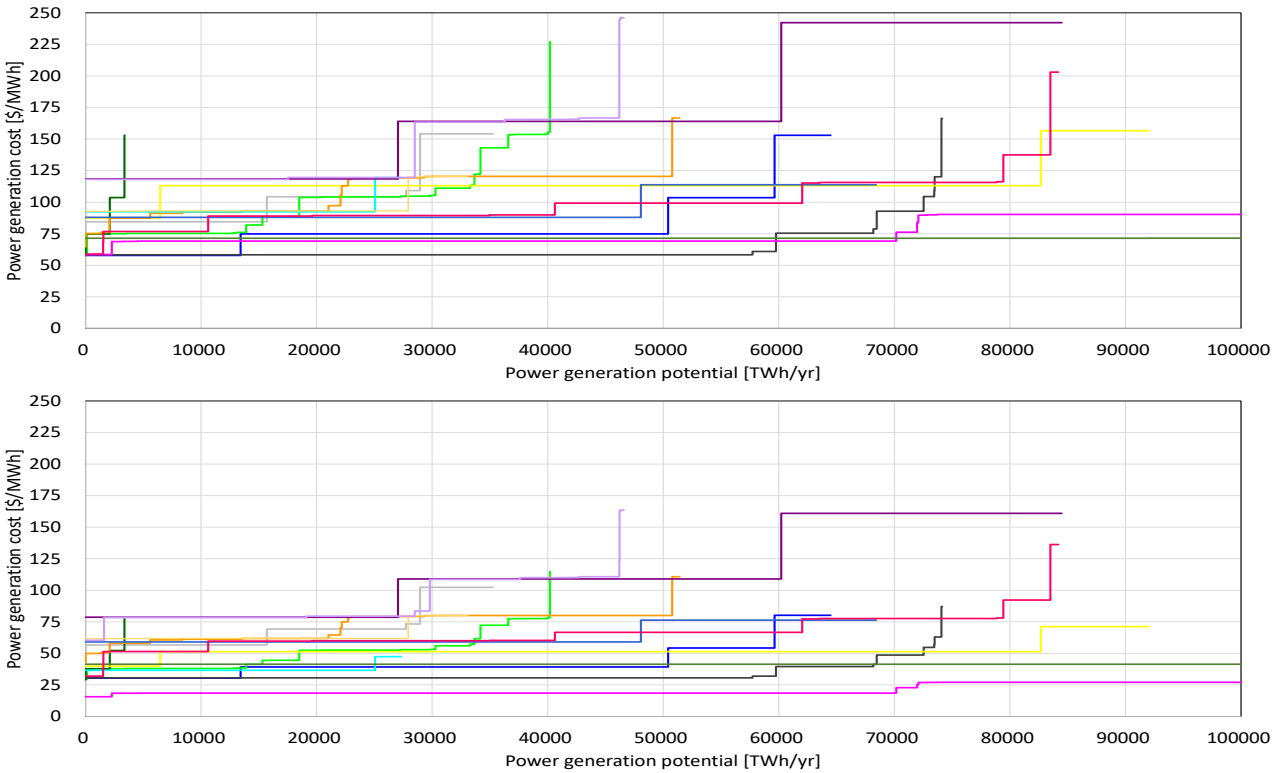


図 2-4 太陽光発電コストの想定（上図：標準、下図：GR シナリオ）

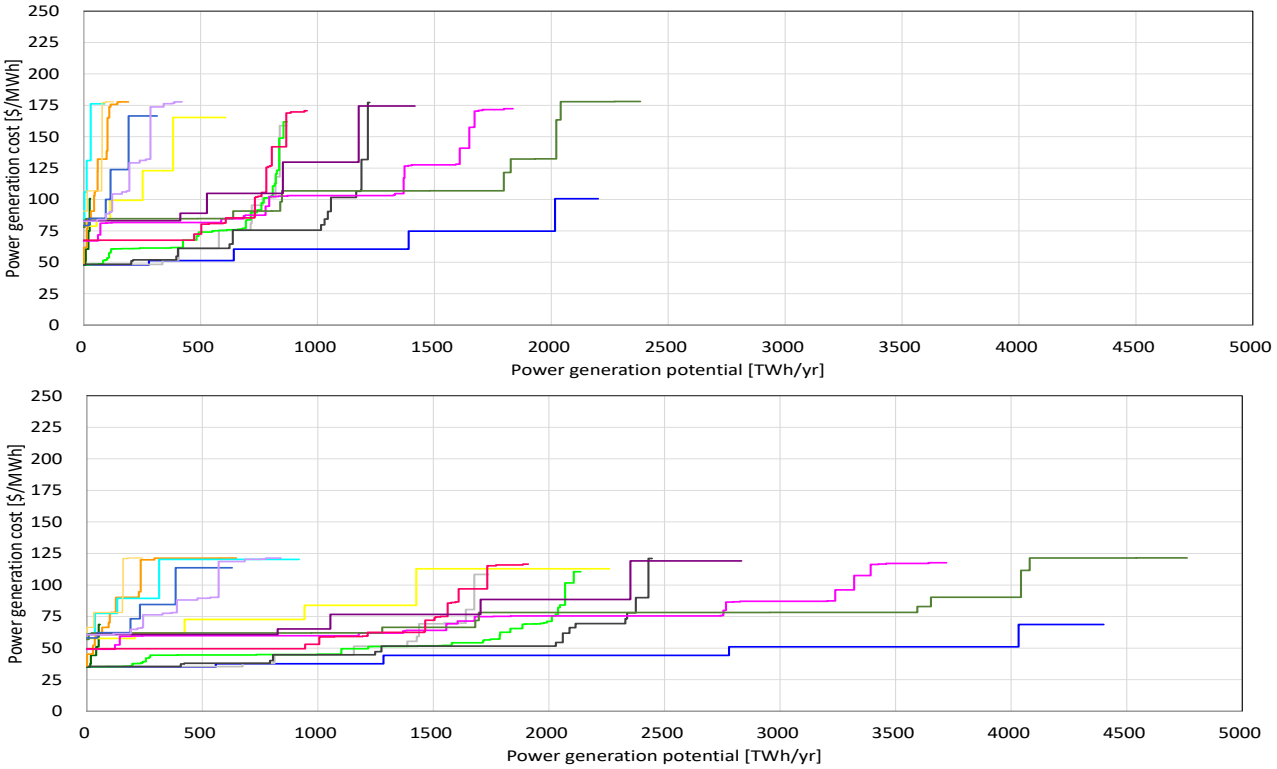


図 2-5 風力発電コストの想定（上図：標準、下図：GR シナリオ）

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

2.3.1　DX 等の需要対策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 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を示す。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 2-7 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を示す。また、B2DS シナリオ、15DS シナリオについて、標準シナリオ（Std）からの世界の GHG 排出量の低減を図 2-8 に示す。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。

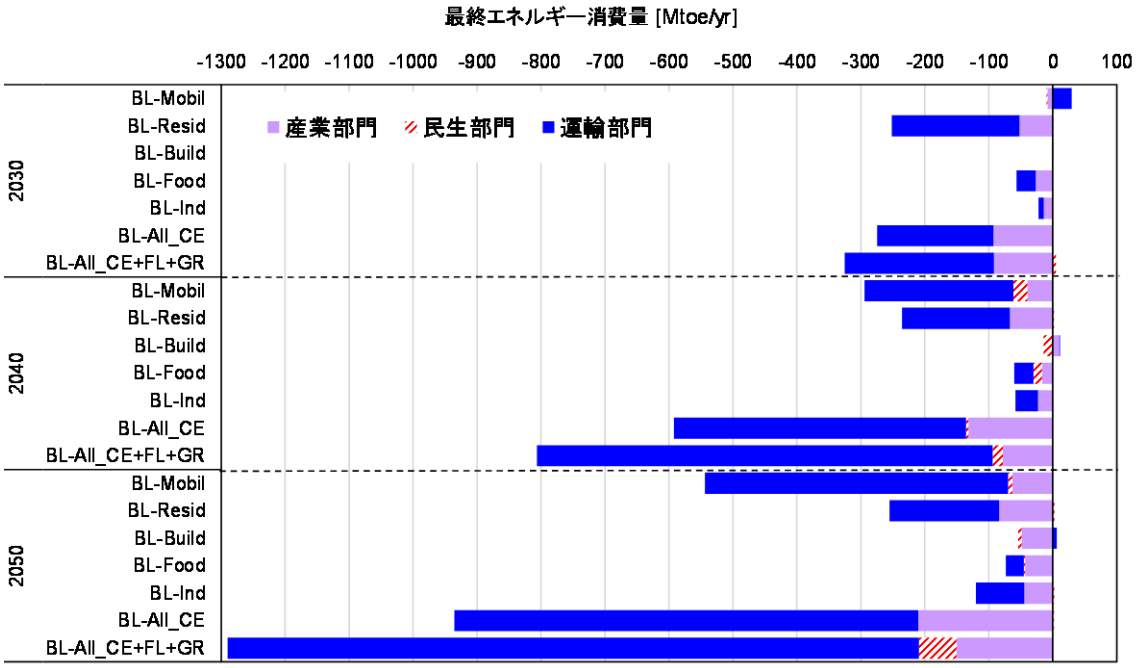
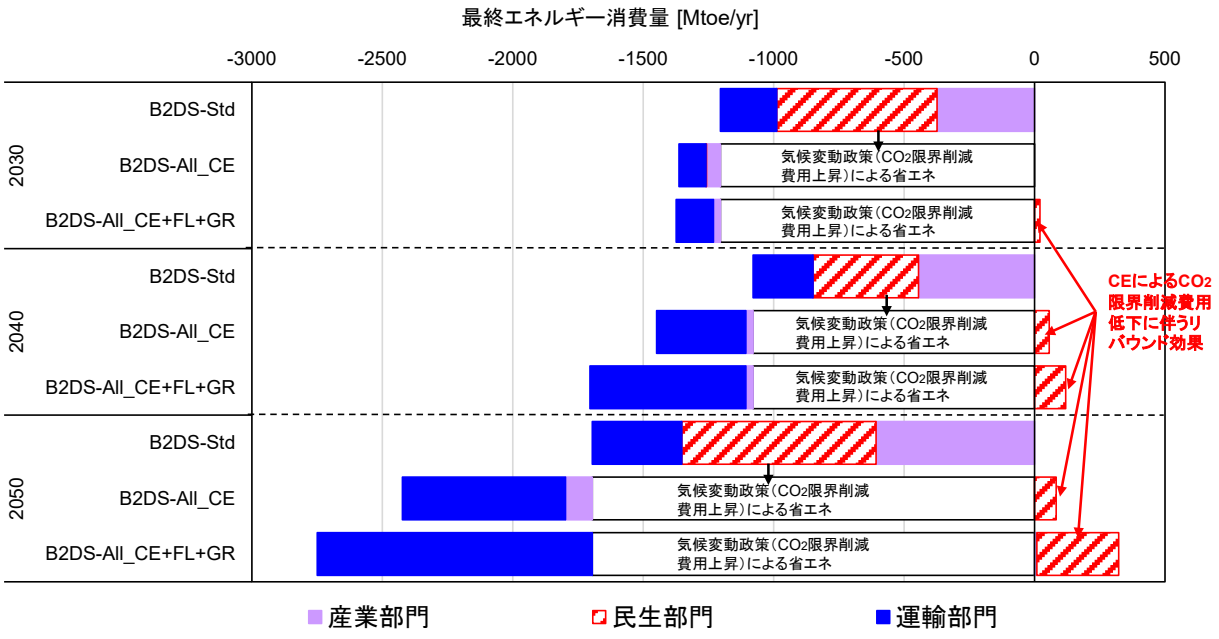


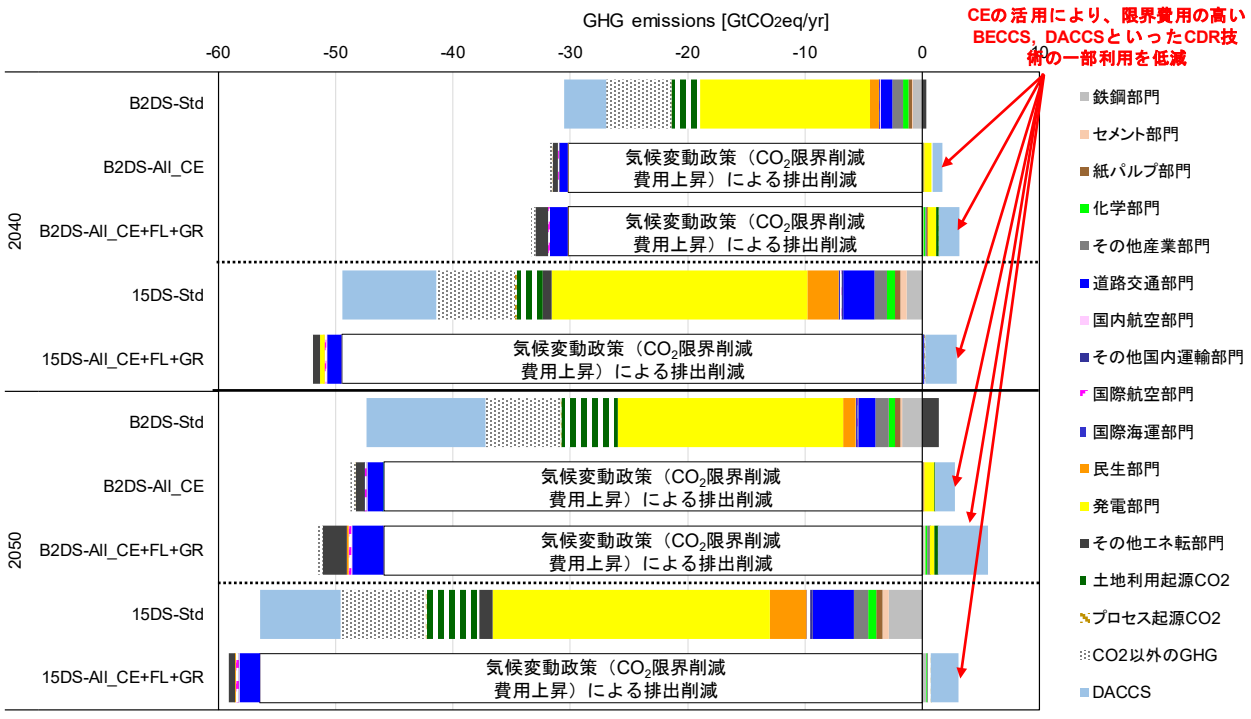
図 2-6 世界エネルギー消費量（ベースラインシナリオ、CE 想定時の変化）

① RITE



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 2-7 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 2-8 世界の GHG 削減効果（B2DS（2℃制約シナリオ）および 15DS（1.5℃制約シナリオ）下、CE想定時の変化）

図 2-9 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。

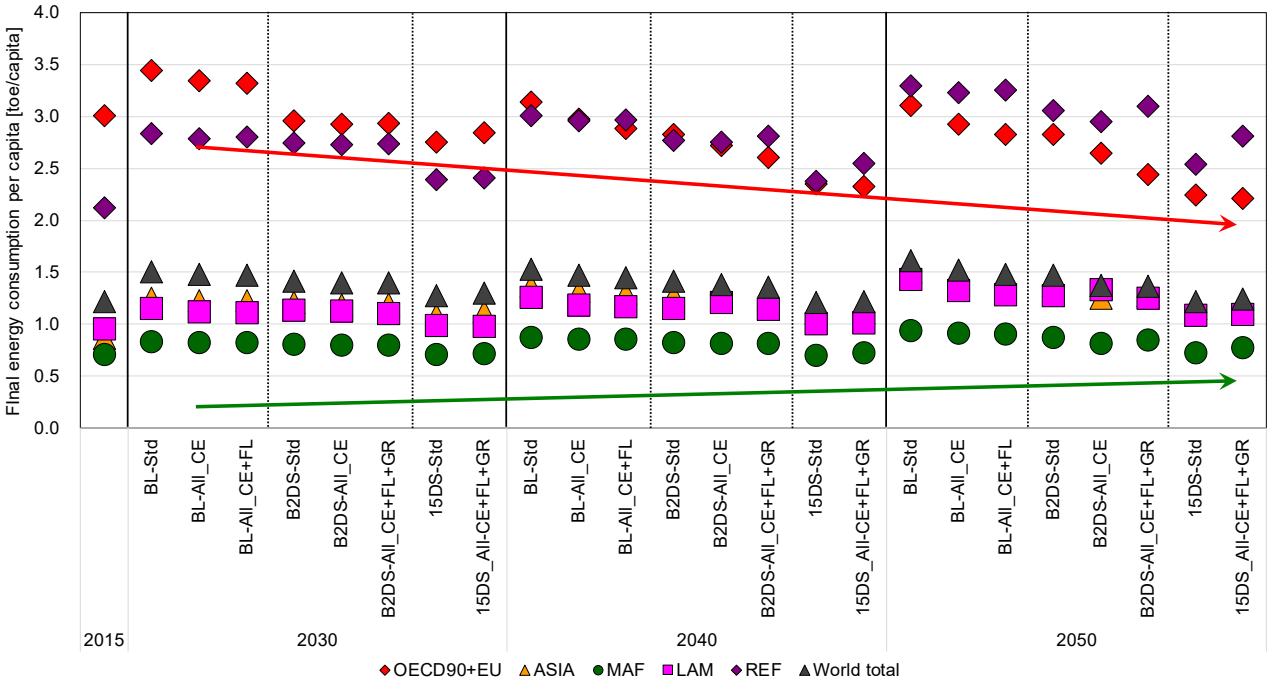


図 2-9　世界地域別の一人当たり最終エネルギー消費量

2.3.2　DX 等の需要対策によるコストへの影響試算

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 および 15DS 時の CO_2 限界削減費用を示す。DX によって誘因され得る 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、1.5℃目標といった長期目標の実現においては、CO_2 限界削減費用の低下が期待できる。

表 2-7　ベースラインおよび B2DS 時の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 および 15DS 時の CO_2 限界削減費用（単位：USD/tCO_2eq）

	2℃（>66%）：B2DS				1.5℃：15DS	
	B2DS-Std	**B2DS_All-CE**	**B2DS_All-CE+FL**	**B2DS_All-CE+FL+GR**	**15DS-Std**	**15DS_All-CE+FL+GR**
2040 年	68–310	57–238	57–240	50–195	550	344
2050 年	146–739	123–524	122–522	60–364	513	225

※ 限界削減費用の幅は国による差異

2.3.3　需要側対策を中心とした削減貢献量の試算

本節では、”avoided emissions”として、需要側対策の排出削減効果を明示的に分離して推計した試算結果を示す。図 2-10 は、BL-Std シナリオの排出量から、B2DS-All_CE への排出削減効果を、特に DX によって誘発され得るサーキュラー経済等を通しての貢献量や、その他（家庭用ヒートポンプ等）の貢献量を明示したものである。発電や DACCS の排出削減効果は大きいものの、一定の効果がある。また、これら対策は DACCS 等に比べ比較的費用が安価な対策となっている。いずれにしても、このような”avoided emissions”を見える化していくことは大変重要と考えられる。なお、今回の分析では、限定的な対策およびその波及効果の考慮に留まっているため、今後、より広範に評価範囲を広げることが重要であり、その際には、今回試算した削減貢献量よりも、大きな貢献が推計される可能性は高い。

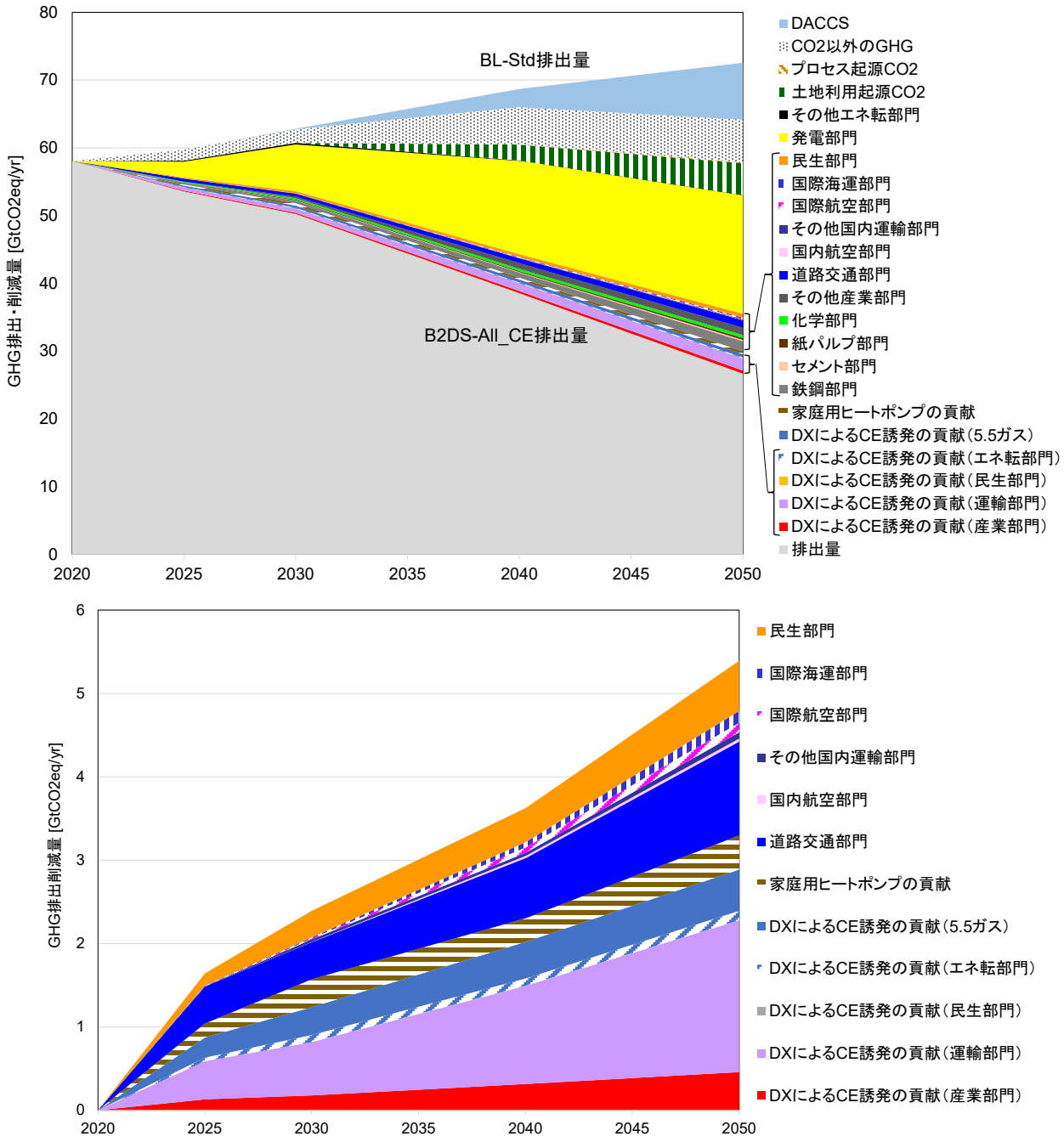


図 2-10 世界の GHG 排出削減への貢献量（上図：全体、下図：最終需要部門対策の削減効果（aovided emissions）の抜粋）

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。また、1.5℃シナリオ（15DS シナリオ）についても、評価を行った。これらの分析は、EDITS の model complementary exercise (MCE) の 1 次試算としても提供し、複数の分析との比較にも活用した。

また、排出削減貢献“avoided emissions”は、製品・サービスを通しての排出削減への寄与を見える化しようとするものであり、需要側対策の評価 EDITS との関連性は深い。今年度は、その定量的な評価にも取り組んだ。波及効果を含めて、他方、合理的に、過不足なく貢献量を算定することで、こういった企業・社会の取り組みを後押しすることにもつながると考えられる。

なお、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。

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Modeling and implementing sufficiency to achieve high well-being with low energy demand

Jingjing Zhang1, Nina Khanna1, Michelle-Johnson Wang[1,2], Nan Zhou[1]
[1] Lawrence Berkeley National Laboratory
[2] University of California, Berkeley

Abstract
The global energy crisis, escalating security concerns, economic instability, and the intensifying impacts of climate change compel us to reconsider the development pathways and rethink our current production and consumption systems. In light of these challenges, the concept of energy sufficiency has gained significant momentum, particularly since its introduction in the 2022
IPCC report. Since then, a growing body of scholarly work has emerged, offering philosophical implications, frameworks, policies, and data to develop the concept of sufficiency further. At its core, energy sufficiency aims to limit absolute energy consumption within the planetary boundaries while ensuring the fulfillment of social foundation and well-being. Despite its straightforward premise, the field of sufficiency research is still in its early stages. A literature review reveals that most studies remain theoretical, and the practical application of the sufficiency concept is highly challenging. This paper introduces a novel framework, "DAMS" (Decentralization, Adjustment, Moderation, and Sharing), to facilitate the implementation of energy sufficiency. DAMS outlines tangible steps for applying sufficiency across various demand-side sectors and contexts, supplemented with illustrative examples. The framework can help inform energy modelers in scenario design and policymakers in energy transition and decarbonization planning. It also helps to prompt follow-up actions and shift the sufficiency narratives and paradigms among policymakers, manufacturers, designers, consumers, and the research community.

Keywords
Modeling, Energy Sufficiency, Well-being, Low energy demand

Closing the information gap for implementing ambitious mitigation: what works at what costs

Prepared by Lawrence Berkeley National Laboratory: Jingjing Zhang, Michelle Johnson-Wang, Hon Leung Curtis Wong, Nan Zhou*

In collaboration with Asian Institute of Technology: Joyashree Roy, Shreya Some, Huzaifa Butt and others including Eric Masanet[1], Leila Niamir[2], Luis Martinez[3], Souran Chatterjee[4], BOZA-KISS Benigna[5]

[1.] University of California, Santa Barbara
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Abstract
The transition to achieving net-zero emissions by 2050 necessitates a substantial increase in investment in the energy system, which includes the energy supply and demand sectors, and infrastructure. However, many countries and regions worldwide are still grappling with a significant shortfall in the climate mitigation financing. Meanwhile, as understanding of the cost advantage progresses, governments, investors, and individuals are increasingly advocating for renewable energy targets. Previous research has shown energy service demand-side solutions have high mitigation potential with multiple benefits but underscores a significant knowledge gap: the absence of comprehensive, comparable real-world cost estimates. Here we
present a comprehensive transparent data library to bridge the information gap. What sets this paper apart is the immense effort in scrutinizing facts and figures from real-world implementation costs and saving potentials for both developed and developing countries across all continents and presenting them in a comparable framework. We identify energy services,
alternative options of satisfying them, associated costs and with estimated potential for energy savings, and CO2 emission reduction. Results demonstrate immense relative cost advantage. Over 50% savings in costs, emissions and energy compared to baseline are available in both developed and developing countries for multiple demand side solutions.

Key words: Human well-being, Demand for energy services, Climate mitigation, mitigation costs and potential, avoid-shift-improve, Technology-behavior-infrastructure

EDITS

Energy Demand changes Induced by Technological and Social innovations

WP2 Data deliverable

A data mapping exercise to identify key data gaps in the description of Low Energy Demand Pathways

EDITS

2024-01-28

Authors: Oreane Edelenbosch
Utrecht University

Abstract

This report primarily describes the progress made in the EDITS data mapping exercise in identifying key data gaps that need to be overcome to strengthen the description of Low Energy Demand (LED) Pathways. The data mapping has been a cross sectoral group effort that provides an extensive overview of what demand side data is available in the literature. The available data is mapped over strategy, method and region showing clearly where data gaps exist and providing a roadmap for future demand side research. The results show that the majority of data has a European focus while there is a lack of data in Africa and South America. In China and India almost half of the local and national studies research the improve strategy, which is more common than in other regions. The report continues to provide a general description of the work package aims and goals, and the role that identifying the key data gaps plays in achieving those goals.

③ Utrecht Univ.

Implications of reducing diesel demand in Brazil's transport sector for meeting the country's climate goals*

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[1] *Centre for Energy and Environmental Economics (CENERGIA), Energy Planning Program, COPPE, Universidade Federal do Rio de Janeiro, Brazil*

**This report was also submitted for publication in "Energy – The International Journal" on January 4th, 2024*

***Corresponding author: Roberto Schaeffer*

A B S T R A C T

Given its usage in freight and urban transportation, diesel supply is a major global issue. Diesel dependence and the urgency of the energy transition are normally addressed on the supply side by either expanding oil refineries or evaluating alternative fuels. Here we focus on the demand-side by examining how road pavement conditions and eco-driving practices affect diesel fuel consumption on highways. This can be particularly important in emerging countries, where road pavement is normally not well-managed and conserved. This analysis encompasses six scenarios for Brazil that vary in road conditions, driving cycles, and tire inflation states. Findings show a significant potential for

annual diesel savings, reaching 4.52 billion liters. A financial analysis indicates a positive return by the year 2037. Hence, this study emphasizes the need for a multidimensional approach to reduce fuel consumption and enhance environmental sustainability within the transportation sector of an emerging economy. While infrastructural improvements are crucial, their effectiveness is greatly amplified when paired with efforts in driver education.

Keywords: Road Pavement Conditions; Eco-driving; Fuel Consumption; Sustainable Transport Policy

Highlights

- Road condition improvements and eco-driving practices can reduce diesel consumption
- Annual savings of up to 4.52 billion liters of diesel are possible in Brazil
- Economic analysis indicates a positive net present value for road recovery efforts
- Pavement recovery economic feasibility varies across road segments

Final Report

Energy Demand in South and South-East Asian countries:
Decoupling status, Modelling Approaches and Socio-technical & Cultural Transitions.

Submitted by
Asian Institute of Technology, Thailand
PI: Joyashree Roy
Director
Centre for South and South-East Asia
Multi-Disciplinary Research Network on Transforming Societies of Global South,
Asian Institute of Technology, Pathumthani 12120 Thailand.

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 IV

Project period: June 1, 2023-March 29, 2024

Report period: June 1, 2023-February 29, 2024

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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 2023 at Lisbon, Portugal: Joyashree Roy participated in person in the Annual EDITS Workshop held in November 6-10, 2023, and actively contributed to the discussion sessions and social events and from the team, Md. Huzaifa Butt participated online.

c. COP 28
   - Joyashree Roy was a speaker at the RITE-IIASA organised EDITS side event at COP 28 to discuss "Demand-side solutions to disruptions" held in Japan Pavillion on 11. 12. 2023. https://iiasa.ac.at/events/nov-2023/iiasa-at-cop28. Title of presentation: "The costs and potentials of demand-side interventions from a Global South perspective".
   - Joyashree Roy as chair of Climate Strategies participated at Climate Strategies' Members & Friends Event at COP28: Key research priorities to support climate policy held on 11. 12. 2023. (Annexure1).

d. AIT participants in IIASA-WG(s):
   Industry (Joyashree), Buildings (Huzaifa), Data (Shreya, Huzaifa, Joyashree), Protocol (Joyashree, Shreya, Firuz).

e. Fast track paper activities: Participation from AIT
   With LBNL: data, metric and costs and potentials (Joyashree, Huzaifa, Shreya)

1.2. Workshop/conference panel organised

Organised and Moderated Joint Special Panel Discussion on "IDEEA –Indian Zero Carbon Pathways" at INSEE Biannual conference in India in collaboration with Global Change Programme, Jadavpur University, Kolkata, IISC Bangalore, IIT Roorkee, India. (Annexure :2)

1.3 Presentation in other relevant workshops/seminars/conferences

Joyashree Roy:

a. Moderated a Panel discussion on "Demand side solutions and mitigating climate change" organised by INSEE and Jamia Millia Islamia University, India on 5 June 2023 with two other EDIT colleagues: Keigo Akimoto and Leila Niamir. (Annexure 3)

b. Invited and participated in 2023 breakthrough dialogue on Metabolic rift in USA California, June 21-23, 2023.
https://thebreakthrough.org/events/2023-dialogue-metabolic-rift

c. Presented Keynote address at the launch and annual workshop of Indian Zero Carbon Pathway (IDEEA model) – Noida, India, organized by IIT Roorkee and EDF, August 21st-23rd. (Annexure 2)

d. Delivered online invited lecture on Economics of Disaster Organised by IIT-Guwahati, August 10th and 17th.

e. Delivered Invited online Lecture on Climate Change and Economic Opportunities for South Asia, Organised by IMPRI, India, August 12th

f. Delivered Invited online speech in inaugural session on Just transition in Bangladesh, Organised by ULAB, August 27,2023

g. Delivered speech (in-person) on "The state of climate science and policy" and participated as expert in "From Science and Policy to Action: Panel Discussion", Mekong Environmental Resilience Week 2023, September 13 - 15, 2023, in Bangkok on September 14, 2023 organized by SEI.

h. Delivered invited talk on "Challenges in opportunities in transmission: global and local perspectives", at Science day organised by EDF, New York city, USA on 04 October 2023

i. Participated in Global Plastics Summit, organized by The Economist, 11- 12 October 2023, Bangkok, Thailand

j. Delivered invited talk on "Technological Innovation System for Circular Plastic Economy" prepared jointly with Post Doc Dr Satabdi Datta, at the Circular Systems Innovation for Flexible Polyurethane Foam Waste Workshop, organized by AIT, in collaboration with the University of Cambridge and nornnorn, 19 October 2023, Bangkok, Thailand

k. Presented on "Transformation through decoupling in South Asia" at Potential of alternative development and Growth Futures: Global South and Emerging economies, Germany (virtual), 25 October 2023

l. Presented on "Role of Circular Economy in Climate change Crisis", South Korea (virtual), 26 October 2023

m. Delivered talk on "What is wellbeing in the Global South and how to achieve it" and moderated the session on "EDITS innovations to fill in research gaps", at EDITS Annual Meeting, 6-10 November 2023, Lisbon, Portugal

n. Understanding the Multi-dimensional Challenges for sustainability transitions, Presented at the Virtual Annual Meeting of LCS-RNet on December 19, 2023.

2. Publications:(published with acknowledgement to EDIT)

- **Butt Huzaifa, Joyashree Roy, S Some (2024) Policy as a catalyst in shaping mobility sector transition for developing countries, Environ. Res. Lett. 19 024039, DOI 10.1088/1748-9326/ad1d29. https://iopscience.iop.org/article/10.1088/1748-9326/ad1d29/pdf**

Abstract: This paper presents a modified technology innovation system (MTIS) approach applicable to developing countries. Evidence collected over three decades 1992–2022, shows how policy plays a catalytic role in managing multidimensional low-emission mobility transitions in developing countries such as Pakistan. This paper follows policy and the network of actors, institutions and technology in compressed natural gas (CNG)-based mobility transition in Pakistan. Event-based analysis helped in mapping the development of respective functions, which is later validated by expert consultation. Between 1992 and 2002, deliberate policies for early adoption were put in place to strategically manage a desired transition path. This involved providing guidance and knowledge diffusion through demonstration to increase entrepreneurial activities and market formation. The accelerated diffusion during the take-off period during 2003–2012 was due to the entry of private businesses and multinational companies speeding up entrepreneurial activity and market-formation functions. However, there was a clear policy-driven roll-back and deceleration during 2013–2022. Policies designed to ban CNG license issuance and renewal resulted in detrimental effects on market and entrepreneurial activities. Social struggle arising from roll-back is now caught in a dilemma if policy innovation will lead to re-emergence of CNG or will support a new transition cycle through the emergence and adoption of electric vehicles in the mobility space of Pakistan. Rapid shifts in the global landscape of innovation and market conditions are creating a need for the effective handling of cascading transition management in developing countries. This paper outlines how lessons learnt from Pakistan's CNG-MTIS can help in shaping electric vehicle MTIS not only in Pakistan, but also in many other developing countries. It is recommended that, in order to manage cascading transitions in developing countries, new approaches and strategies for reskilling, retraining and redirecting finances to address stranded assets be employed. This can mitigate the negative impacts on those affected by transformation and create an environment for a just transition that restores trust in policy and accelerates transformative change. (Annexure 4)

- **Masahiro Sugiyama, Charlie Wilson, Dominik Wiedenhofer, Benigna Boza-Kiss, Tao Cao, Joyee S. Chatterjee, Souran Chatterjee, Takuya Hara, Ayami Hayashi, Yiyi Ju, Volker Krey, María Fernanda Godoy León, Luis Martinez, Eric Masanet, Alessio Mastrucci, Jihoon Min, Leila Niamir, Setu Pelz, Joyashree Roy, Yamina Saheb, Roberto Schaeffer, Diana Ürge-Vorsatz, Bas van Ruijven, Yoshiyuki Shimoda, Elena Verdolini, Frauke Wiese, Yohei Yamaguchi, Carina Zell-Ziegler, Caroline Zimm (2024) High with low: Harnessing the power of demand-side solutions for high wellbeing with low energy and material demand,**

Joule,Volume 8, Issue 1, 2024, Pages 1-6,ISSN 2542-4351, https://doi.org/10.1016/j.joule.2023.12.014.

Abstract: The authors are all devoted energy system and sustainability transformation scholars, who collaborate regularly and actively at global and local levels to advance the knowledge space of demand-side solutions and policies. They are members of a growing bottom-up initiative, the Energy Demand Changes Induced by Technological and Social Innovations (EDITS) network (https://iiasa.ac.at/projects/edits), which builds on various research disciplines to facilitate advances in modeling, data compilation, and analysis of the scope and breadth of the potential contributions of demand-side solutions for climate change mitigation, improved wellbeing for all, and sustainability, complementing supply-side solutions for de- carbonizing the energy and ma- terial systems.

- **Mahmud, H., Roy, J. Energy sector sustainability for a fast-growing economy like Bangladesh: an empirical assessment. Sustain Sci (2023). https://doi.org/10.1007/s11625-023-01385-2**

Abstract: Fast-growing economies like Bangladesh are expected to experience high growth in GDP, and in energy use with structural shifts towards digitalization and industrialization in the coming decades. However, given the goal of global net zero carbon growth, energy sector development will need to satisfy multiple sustainability criteria simultaneously. This paper examines empirically the trends in sustainability indicators for Bangladesh's energy sector to assess the current status based on past trend. A long list of 438 indicators is compiled from the literature used in various country contexts for understanding energy sector sustainability but this study identifies a short list of 38 Bangladesh-specific indicators and develops a composite index. Principal Component Analysis (PCA) method was used for weighting individual indicators to arrive at the composite index. Results show that Bangladesh is showing marginal progress towards sustainability of the energy sector. While progress in social and economic indicators such as increasing access to cleaner fuel, electrification, productive use of energy, increased diversity of fuel mix has aided in advancing sustainability, the deteriorating environmental indicators over time is pulling down the sustainability status of the energy sector. Among other things, increasing share of fossil fuel in energy mix, lack of adequate improvement in energy efficiency in all sectors, increase in methane emissions need attention and solution to make energy sector sustainable. These steps can also help in reducing overall energy demand and emissions without adversely impacting social and economic growth through deployment of appropriate fuel choice, technologies and infrastructure. For better monitoring of energy sector sustainability, some data gaps for Bangladesh have also been identified. (Annexure 5)

- **Mahmud Hasan and Joyashree Roy (2023): What to focus on in order to accelerate access to modern energy services and energy use efficiency in Bangladesh, Asia-Pacific Sustainable Development Journal Vol. 30, No. 1, May 2023. https://www.unescap.org/kp/2023/asia-pacific-sustainable-development-journal-vol-30-no-1-may-2023. ISBN:978-92-1-101477-8.**

Abstract: Consistent with national priorities: How can a rapidly growing country, such as Bangladesh, overcome the barriers to realizing Sustainable Development Goal 7? The present study includes an analysis of the barriers to achieving 24x7 access to modern energy and the required improvements to make energy more efficient to overcome them in Bangladesh. Interpretive structural modeling (ISM) is applied to identify the interactions among the barriers as laid out in context-relevant scientific literature. The Cross- impact matrix multiplication applied to classification (MICMAC) is applied to classify the barriers. The results indicate that the barriers can be addressed through a systematic packaging and prioritization approach. (Annexure 6)

- **Kumar Anil, I Pal, Joyashree Roy, Nonthakarn Benjachat and Kittinut Pimpakhun (2023), Critical infrastructure resilience in Eastern Economic Corridor of Thailand -a review, In Multi-hazard vulnerability and resilience building: cross cutting issues, ed. By I Pal and R Shaw, Elsevier, Netherlands. ISBN: 978-0-323-95682-6.**

Abstract: Thailand encourages investments to upgrade industries and increase competitiveness, enabling the economy to grow. The government of Thailand notified the development of EEC as a major infrastructure development zone in the Chonburi, Rayong, and Chachoengsao provinces. High economic activity has led to massive infrastructure development in the region. At the same time, geographical location, hazard potential, increasing population density, and huge infrastructure development make EEC a potential risk zone in the country. Existing, and planned critical infrastructure are under threat of various risks induced by natural hazards, industrial accidents, and cyberattacks. For the critical infrastructure sector, disasters lead to ripple and cascading impacts on other key sectors of society. To minimize the ripple effect on key economic and social sectors of the economy, risk mitigation and management approaches are required to be implemented. Risk mitigation and management starts with the risk assessment as well as identification of critical infrastructure. Furthermore, identification of the critical infrastructure sector is a challenging task. Criticality criteria play an important role in identifying infrastructure as critical infrastructure. Similarly, the complex and interdependent nature of critical infrastructure systems make the risk assessment process cumbersome. (Annexure 7)

3. Work in Progress

a. Bottom-up country specific study on decoupling status.
b. Popular media Communication and energy demand.
c. Sufficiency Principle in practice South-east Asian Region

Annexure 1

Climate Strategies' Members & Friends Event at COP28

Key research priorities to support climate policy

Date: Monday, 11th December 2023 (2-3pm GST)
Location: Blue Zone (Exact location TBC)

1. **Welcome from Climate Strategies' Chair Joyashree Roy**

2. **Speed presentations by Climate Strategies' Secretariat and Members.**
   Topics will include: Oil and gas transitions, Trade, Economic modelling, Urban development & more.

- Gintarė Zinkevičiūtė – CS Secretariat
- Olga Chepelianskaia – CS member
- Michael Mehling – CS member
- Adriana Chavarría-Flores – CS Secretariat
- Simon Sharpe – CS member
- Michael Grubb – CS member
- Ines Jimenez Rodriguez – CS Secretariat
- Joyashree Roy – CS Chair

3. **Discussion on key research priorities to support climate policy**

4. **Conclusion from Climate Strategies**

Attendee List

Members of Climate Strategies

- Olga Chepelianskaia
- Michael Grubb
- Michael Mehling
- Joyashree Roy
- Simon Sharpe

Partners & Friends (TBC)

- Adrian Fernandez and Jorge Villarreal, Iniciativa Climatica
- Climate Works
- Global Challenges Foundation
-

Climate Strategies at COP28

View our full list of events here: COP28 - Climate Strategies

Follow our social media channels for the latest updates:

LinkedIn: https://www.linkedin.com/company/climate-strategies

X: X (twitter.com)

IDEEA
Indian Zero Carbon Energy Pathways

Annexure 2

Launch of IDEEA
Indian Zero Carbon Energy Pathways
Agenda – 23rd August 2023

Venue: GNEC-IIT Roorkee, Plot No. 20, Knowledge Park II, Greater Noida, Uttar Pradesh 201310
https://goo.gl/maps/3vBYD9P5VBGSLdcCA

Time	Session title
9:00 – 9:30 AM	**Registration**
9:30 - 9:35 AM	**Welcome address.** *IIT Roorkee* *Prof. Usha Lenka (Online), Head - Department of Management Studies*
9:35 – 9:55 AM	**Special Address** • *Role of Models for India's Energy Security – Prof Balachandra Patil, Chief Research Scientist, Indian Institute of Science, Bengaluru* • *How IDEEA is more than a model – Prof Joyashree Roy, Founder Advisor, Global Change Program – Jadavpur University and Director, SMARTS Centre, Asian Institute of Technology, Thailand*
9:55-10:00 AM	**Welcoming the Chief Guest; and about IDEEA** *Hisham Mundol, Chief Advisor, Environmental Defense Fund*
10:00 – 10:10 AM	**Address by Guest of Honor** *Shri Tarun Singh* *Deputy Secretary, Ministry of New and Renewable Energy (MnRE)*
10:10 – 10:20 AM	**Address by Guest of Honor** *Shri Dilip Chenoy* *Chairman – Bharat Web3 Association and Former Secretary General FICCI*
10:20 – 10:25 AM	**Launch by the Chief Guest followed by video**
10:25-10:30 am	**Address by Chief Guest** *Shri Dinesh Dayanand Jagdale** *Joint Secretary, Ministry of New and Renewable Energy*
10:30 -10:35 am	**Vote of Thanks and invite the inaugural panel for the launch.** *Parthaa Bosu* *Lead Advisor – India, Environmental Defense Fund*
10:35 am	**Felicitation of all guests**
10:35 – 11:00 am	Networking tea break
11:00 - 12:00 am	**Role of models in states and national decarbonisation strategies** ***Moderator:*** *Dr Balachandra Patil* ***Panelists:*** 1. *Dr Ritu Mathur, Consultant, NITI Aayog, New Delhi* 2. *Mr Ravindra Kadam, Senior Advisor Renewable Energy, CERC, New Delhi* 3. *Mr Venu Gopal Mothkoor, Senior Specialist, Director, NITI Aayog* 4. *Dr Rohit Bhakar, Associate Professor, Malaviya National Institute of Technology, Jaipur*

12:00 – 1:00 pm	**How Indian modelling capacity can help empower business, policy makers on optimal energy mix and decision making.** ***Moderator:*** *Dr Joyashree Roy* ***Panelists:*** 1. *Mr Abhishek Ranjan, Senior Vice President, Climate Connect Digital* 2. *Dr Abhinav Jindal, Senior Faculty at NTPC Power management institute* 3. *Mr Srihari Dukkipati, Research Fellow, Prayas* 4. *Dr Probal Ghosh, Assistant Director, Integrated Research and Action for Development (IRADe)*
1:00 – 1:15PM	**Summary and concluding remarks.** *Mr Mitavachan Hiremath, SusPoT – Centre for Sustainability*
1:15PM onwards	Networking Lunch

***TBC – to be confirmed**

Annexure 3

On the occasion of World Environment Day

DEPARTMENT OF ECONOMICS, Jamia Millia Islamia

&

INSEE
Indian Society for Ecological Economics

Cordially invites you to a PANEL DISCUSSION by IPCC authors on

Demand side solutions for Mitigating Climate Change

PANELISTS:

Leila Niamir (IIASA-International Institute for Applied Systems Analysis, Austria)
Diana Urge-Vorstaz (CEU-Central European University, Hungary/Austria)
Keigo Akimoto (RITE-Research Institute of Innovative Technology for the Earth, Japan)

MODERATOR:

Joyashree Roy (AIT-Asian Institute of Technology, Thailand, Jadavpur University, India and INSEE)

CO-CHAIRS:
Asheref Illiyan, Dept of Economics, Jamia Millia Islamia
Nilanjan Ghosh, Observer Research Foundation and INSEE

VOTE OF THANKS:
Nandan Nawn, Dept of Economics, Jamia Millia Islamia and INSEE

5th June, 2023 (Monday)

TIME: 10:00-11:00 hrs Central European Time / 13.30-14.30 hrs Indian Standard Time
15:00-16:00 hrs Bangkok time / 17:00-18:00 hrs Japan Time

CONTEXT:

Global warming seriously impacts the human wellbeing. The need for solutions and counter measures was strongly demanded at COP27, held in 2022. Therefore, it is crucial to consider various circumstances in each country and sector to implement genuinely effective measures.

In 2018, the Intergovernmental Panel on Climate Change (IPCC) approved and published the 1.5° C Special Report. This special report presented LED (Low Energy Demand) scenario that realizes low energy demand and social changes and presented that energy demand side solutions generate not only climate benefit but also are synergistic with multiple sustainable development goals (SDGs). The Sixth Assessment Report of IPCC published in 2022-2023 includes a new chapter dealing with the energy demand side assessment and is attracting international attention as it has quantified a very high mitigation potential in comparison to traditional supply side measures alone. All these led to development of an active research community on EDITS (Energy Demand changes Induced by Technological and Social innovations) across regions to better understand the demand side solution issues, quantitatively and comprehensively.

The panel comprising of IPCC authors will present what are these demand side solutions, their mitigation potential, links to wellbeing and what method/models are being used to advance this knowledge.

JOYASHREE ROY is currently the Founder Director of the Centre on South and South East Asia Multidisciplinary Applied Research Network on Transforming Societies of Global South and the Inaugural Bangabandhu Chair Professor (2018-2022, July) at SERD, Asian Institute of Technology, Thailand.

LEILA NIAMIR is currently a Research Scholar with Transformative Institutional and Social Solutions Research Group and Sustainable Service Systems Research Group in Energy, Climate, and Environment at International Institute for Applied Systems Analysis (IIASA), Austria.

DIANA URGE-VORSTAZ is currently Professor at the Department of Environmental Sciences and Policy, Central European University, Hungary/Austria).

KEIGO AKIMOTO is currently Group Leader of Systems Analysis Group and Chief Researcher, Research Institute of Innovative Technology for the Earth (RITE), and Specially Appointed Professor, Institute of Innovative Research, Tokyo, Institute of Technology

ASHEREF ILLIYAN is currently Professor and Head, Department of Economics, Jamia Millia Islamia

NILANJAN GHOSH is presently Director of ORF Kolkata, and the Centre for New Economic Diplomacy, ORF & President, INSEE

NANDAN NAWN is presently Professor, Department of Economics, JMI and Associate Editor of *Ecology, Economy, Society—the INSEE Journal*

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Policy as a catalyst in shaping mobility sector transition for developing countries

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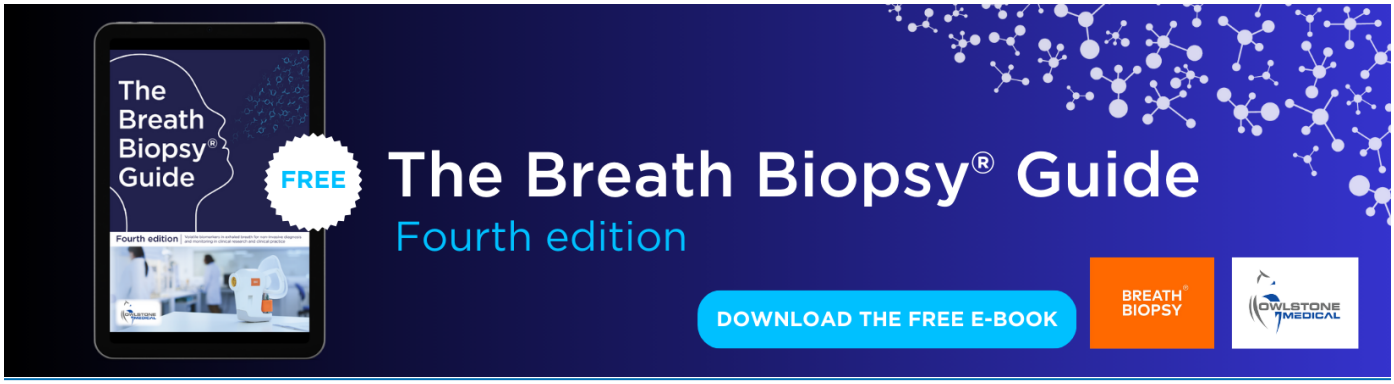

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ENVIRONMENTAL RESEARCH
LETTERS

LETTER

Policy as a catalyst in shaping mobility sector transition for developing countries

Muhammad Huzaifa Butt[1,2,*], **Joyashree Roy**[1] and **Shreya Some**[1]

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Keywords: managing mobility transition, low carbon urban transport, technology innovation system, electric vehicle, just transitions, SDG 7, 17, 9, transition policies

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Abstract

This paper presents a modified technology innovation system (MTIS) approach applicable to developing countries. Evidence collected over three decades 1992–2022, shows how policy plays a catalytic role in managing multidimensional low-emission mobility transitions in developing countries such as Pakistan. This paper follows policy and the network of actors, institutions and technology in compressed natural gas (CNG)-based mobility transition in Pakistan. Event-based analysis helped in mapping the development of respective functions, which is later validated by expert consultation. Between 1992 and 2002, deliberate policies for early adoption were put in place to strategically manage a desired transition path. This involved providing guidance and knowledge diffusion through demonstration to increase entrepreneurial activities and market formation. The accelerated diffusion during the take-off period during 2003–2012 was due to the entry of private businesses and multinational companies speeding up entrepreneurial activity and market-formation functions. However, there was a clear policy-driven roll-back and deceleration during 2013–2022. Policies designed to ban CNG licence issuance and renewal resulted in detrimental effects on market and entrepreneurial activities. Social struggle arising from roll-back is now caught in a dilemma if policy innovation will lead to re-emergence of CNG or will support a new transition cycle through the emergence and adoption of electric vehicles in the mobility space of Pakistan. Rapid shifts in the global landscape of innovation and market conditions are creating a need for the effective handling of cascading transition management in developing countries. This paper outlines how lessons learnt from Pakistan's CNG-MTIS can help in shaping electric vehicle MTIS not only in Pakistan, but also in many other developing countries. It is recommended that, in order to manage cascading transitions in developing countries, new approaches and strategies for reskilling, retraining and redirecting finances to address stranded assets be employed. This can mitigate the negative impacts on those affected by transformation and create an environment for a just transition that restores trust in policy and accelerates transformative change.

1. Introduction

Global assessments have highlighted the need for transformative changes to decarbonize economic activities everywhere, including the transport sector (SLOCAT 2021, IPCC 2022, UNEP 2022). Roy and Some (2022) argued that complete avoidance of all mobility is impractical, as it is a 'service' that connects an interdependent human society by bridging the point of demand to the point of supply. Therefore, it is essential to understand how this 'unavoidable mobility' should be sustainably managed. Understanding how transition is shaped by national policies, which includes national specificities, such as stages of development, changing natural resource endowments, economic wealth, as well as the involvement

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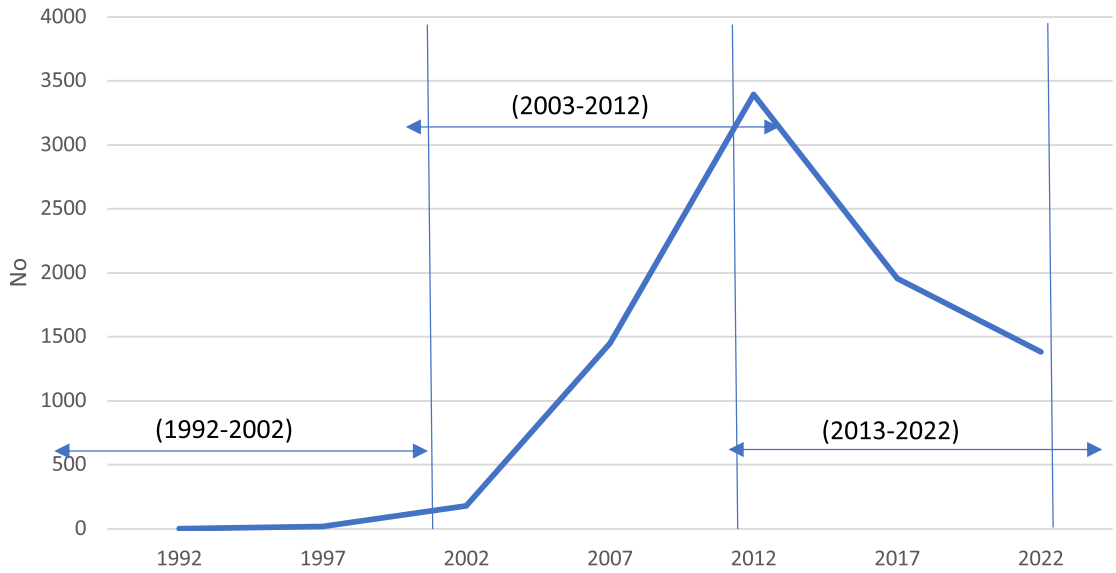

Figure 1. Number of CNG filling stations during 1992–2022. Drawn by authors using data from various sources (oil and gas regulatory authority (OGRA, Pakistan) data for active stations and (Khan and Yasmin 2014)).

of and coordination among different actors (Dubash *et al* 2022, IPCC 2022), helps in identifying and gauging the drivers, opportunities, costs and challenges of such transitions for scaling up and replication. In developing regions, transport-related emissions are rising faster and are expected to rise further in the future. This trajectory contrasts with the situation in Europe and North America, where growth in passenger and freight transport is comparatively more moderate (Jaramillo *et al* 2022). A frequently asked question is, among other social actors, how governments can help in reducing transport energy demand (Jaramillo *et al* 2022). It is important to understand how policy can play an important role in managing multidimensional strategic transformative change in increasing the share of electromobility and low-carbon mobility options. A policy-driven transition towards green technology has occurred in the Netherlands (Suurs *et al* 2010). Understanding the issue from a developing country perspective can provide new, deeper insights for accelerating transition (Butt and Singh 2023). We consider the case of Pakistan (SM1.1) in this paper.

In Pakistan, since 1992 there has been a clear policy-driven process for creating a move away from oil to compressed natural gas (CNG)-based cheap, domestically available cleaner fuel for passenger transport, as reflected in the number of CNG filling stations (figure 1) and the carbon intensity of the sector (figure 2).

This empirical evidence helped us in deciding the stages of the transition, which we discuss in detail in section 2.

From this perspective, this paper tries to answer:

- How government policy can play a catalytic role in deciding technology choice and strategically managing multidimensional transition in mobility service provision through low-carbon fuel-based technology in a developing country context using a case study of Pakistan covering the period 1992–2022.
- How do the various dimensions in the technology innovation system (TIS) framework work in shaping the transition path for developing countries?
- What are the roles of various social actors through various phases ?

This paper contributes significantly on multiple fronts. Firstly, it provides an argument for why the application of the standard TIS framework for developing country context needs to be modified. Secondly, the paper throws light on how policy frameworks can play a critical role in developing countries by deciding on early adopters' roles and thus creating an enabling environment for market development, thereby accelerating the participation of various social actors in infrastructure expansion and technology diffusion. Third, it delineates actions by actors and essential functions crucial for strategically managing the multidimensional transition to low carbon growth. Fourth, the study points out how, for developing countries, there can be overlapping transitions due to internal and external factors and how policy can become critical in providing directionality in transition. Finally, the paper introduces a methodological improvement in the comparative analysis of transition stages by estimating the area under the polygons.

Section 2 outlines the analytical method used in this paper. Section 3 provides the detailed results and section 4 includes a discussion of Pakistan's CNG modified technology innovation system (MTIS), highlighting the role of actors, institutions and

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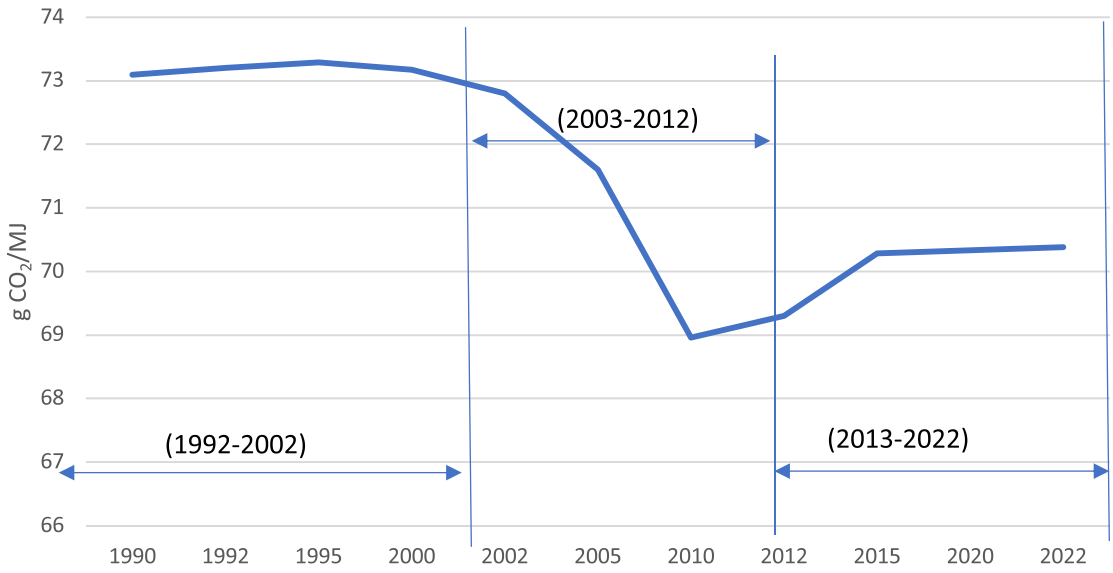

Figure 2. Carbon intensity of road transport in Pakistan during 1992–2022. Drawn by authors using data from the IEA database.

technology through the development of seven functions of the TIS at three stages (decision for early adoption, take-off, roll-back) for CNG-based transport transition in Pakistan, along with a comparison with the Netherlands' automotive natural gas (ANG) TIS. Concluding remarks are presented in section 5.

2. Method: application of the TIS framework

To understand the policies, interventions and actors involved in the CNG-based mobility sector transition in Pakistan, we adopt a multidimensional transition framework (Bergek *et al* 2008, Suurs *et al* 2010, Tigabu *et al* 2015b, Tigabu 2017, Esmailzadeh *et al* 2020) by applying the TIS approach (Jacobsson and Johnson 2000, Hekkert *et al* 2007, Suurs and Hekkert 2009, Wieczorek 2014, Markard 2018, Roy *et al* 2018, Höhne and Roy 2021). The TIS focuses on the roles played by diverse actors, interconnected networks and institutions, coupled with a holistic approach, and has the capacity to offer universally applicable insights (Tigabu *et al* 2015a, 2015b, Tigabu 2017). The TIS methodology is considered as an important framework within the domain of transition studies, primarily due to two reasons: first, the rise of innovative technologies stands at the core of socio-technical transitions. Numerous emerging technologies are constantly challenging conventional technologies, organizational norms and institutional setups. Second, a plethora of contemporary empirical studies utilizing the TIS approach have scrutinized technologies, such as renewable energies and alternative vehicle technologies, that are intrinsically linked to sustainability goals. Literature on the TIS approach has focussed on the intricate micro-level mechanisms underpinning the formation of a TIS. This particularly involves establishing connections with the actor-centred paradigms prevalent in the realm of policy analysis (Sabatier 2014). A frequent criticism aimed at the TIS framework revolves around its limited perspective, insufficient consideration of contextual variables, internal focus and neglect of the broader contextual dynamics of the innovation system (Markard and Truffer 2008). Specifically, there have been assertions that the TIS methodology could potentially overlook the emergence of supplementary or rival technologies within its contextual sphere, as well as the intricate dynamics of competing for supremacy against established technologies. Being aware of these criticisms and given the knowledge of realities in developing countries, particularly Pakistan, we contextualized the method and have classified the barriers into two categories, internal to TIS function—related to actors, institutions and market related to technology—and external to the TIS—e.g. any new emerging competing TIS, which is electromobility (EV-TIS) in our study. We have given special attention to the fact that developing countries require technology transfer rather than initiating an innovation process (Pueyo and Linares 2012). Developing countries in their updated nationally determined contributions (NDCs), mention common challenges and demand a heightened focus on technology transfer mechanisms (e.g. Government of Bangladesh 2021, Government of India 2022, Government of Thailand 2022).

Literature in the context of developed countries mentions four transition stages within the function of the TIS, as presented in supplementary material (SM 1.2). In this paper, to capture the developing country specificity, we combine the first two stages: emergence and early adoption. This decision is based

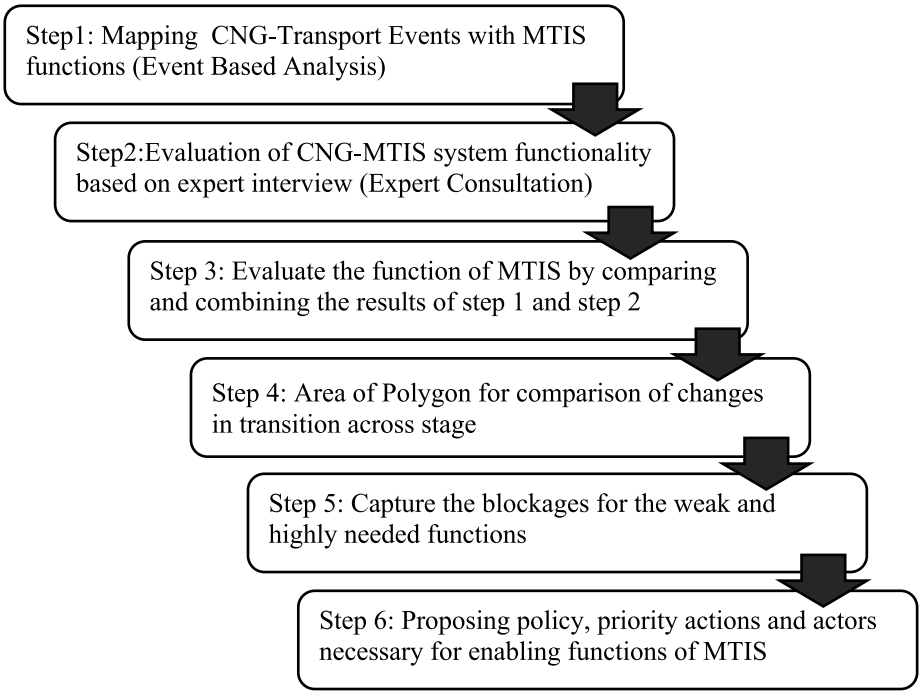

Figure 3. Flow chart of the MTIS methodology.

on the recognition of a fundamental theoretical argument that, due to lack of innovation finance and capacity, developing countries are lagging behind in terms of low carbon technology development (Blanco *et al* 2022). Thus they are 'following' through technology transfer or trade and not 'leading' by innovation. The advantage for developing countries in adopting a follower role in the deployment of low carbon technology is that there is no need to invest significant time and resources in the emergence stage of the technology. By following the established innovation chain, including the critical effort zone, there is no need for extensive trial and error (Hernandez *et al* 2019) to reach maturity and then to find early adopters of the technology. Instead, as a 'follower', a mature low carbon technology can be adopted by skipping the emergence stage. For the follower, the crucial step is to initiate a 'decision for early adoption' of commercial-scale or demonstration-scale technology, thereby taking first-mover advantage among peers and leapfrogging (Mohammed *et al* 2020). In the past, during the introduction and roll-out of clean development mechanism projects for developing countries, China, India and Brazil were able to reap the maximum benefit over their peers in terms of mobilizing projects and fund transfer (Li and Lin 2021) by taking first-mover advantage. This fundamental difference in the roles of developed and developing countries in low carbon innovation dominates the technology transfer argument in multiple international assessments (Ockwell *et al* 2010, Khor 2012, Blanco *et al* 2022) and negotiations. This allows us to modify the TIS by defining and generalizing it for developing countries using 'three' stages of transition instead of the conventional 'four'. The first stage being the 'decision for early adoption' for developing countries – the decade of 1992–2002 for our case study country Pakistan. The second stage is the diffusion stage (hereafter called 'take-off') – the decade of 2003–2012. The decade of 2013–2022 is the 'roll-back' stage. These three stages are reflected very clearly in figures 1 and 2 in section 1. Additionally, by mapping specific decades to different stages, we aim to offer a historical narrative of technological development and the impact of policies in a developing country context. We followed six steps (details are in supplementary material (SM1.2) to assess the CNG-MTIS function, as shown in figure 3.

3. Results

Step-wise results based on event-based analysis and expert consultation are presented in this section. The functional accumulation mentioned in section 2 is utilized to analyse the development of individual functions of the MTIS.

Step 1: Event-based analysis

Figure 4 is a visual representation of the historical development of the seven functions of the MTIS in Pakistan, through three phases: early adoption (1992–2002), take-off (2003–2012) and roll-back (2013–2022). The highest number of events (27) is recorded in the take-off decade (2003–2012) (see SM2 and SM3), which aligns with observations by Khan and Yasmin (2014) that activities in CNG technology space peaked during 2003–2012.

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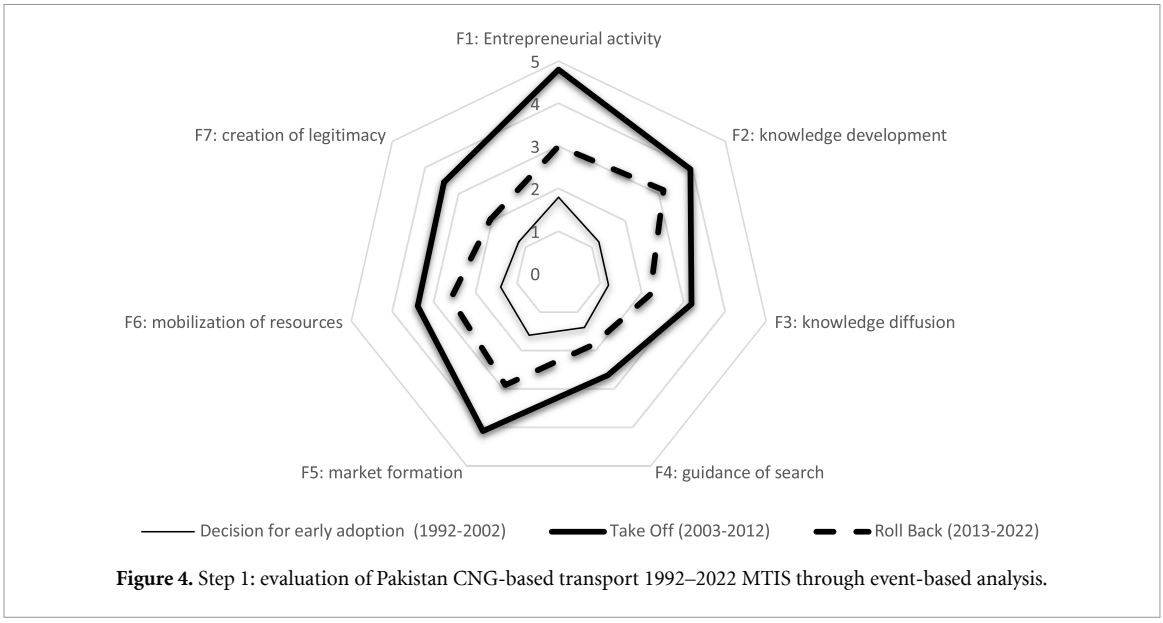

Figure 4. Step 1: evaluation of Pakistan CNG-based transport 1992–2022 MTIS through event-based analysis.

During the 'decision for early adoption' stage (1992–2002), the entrepreneurial and market-formation functions took the lead compared to the others, while the creation of legitimacy, knowledge development and knowledge diffusion functions were the weakest. In the next decade (2003–2012), referred to as the 'take-off' phase, entrepreneurial activity reached its peak. Knowledge development and market-formation functions also improved significantly. The functions of knowledge diffusion, search guidance, mobilization of resources and creation of legitimacy also showed improvement compared to the previous decade, although they remained weaker compared to other functions. The decade 2013–2022, labelled as the 'roll-back' phase, is visibly characterized by the shrinking activities in the CNG-MTIS. This resulted in reductions in the *capability* and *capacity* of the system. Entrepreneurial activity was reduced due to policy roll-backs by the government, such as imposing a ban on issuance/renewal of licences for CNG stations, limiting the production of CNG kits only for export purposes and removal of CNG cylinders in public transport. The exit of relevant actors led to a notable decline in entrepreneurial activity, driven by unfavourable policies. This, in turn, led to a corresponding decrease in the functions of creation of legitimacy, resource mobilization, market formation, and guidance for search and knowledge diffusion, knowledge development has been shrinking at a much slower pace compared to other functions (figure 4).

The comprehensive 30 year policy landscape in Pakistan is summarized in figure 5.

Step 2: Expert consultation

Many actors were associated with CNG's decades-long transition; for instance, private parties, the All Pakistan CNG Association (APCNGA), researchers and a government CNG-specific organization. The experts selected for the consultation in this study are individuals affiliated with the actors involved in CNG technology in Pakistan.. They are from the key institutions of CNG technology, as follows: (1) the Hydrocarbon Development Institute Pakistan (HDIP); (2) the Oil and Gas Regulatory Authority (OGRA) representing the government; (3) the APCNGA representing private parties in CNG businesses; and (4) researchers identified during a review of published literature (SM4 and SM5).

Figure 6 shows that, in the early adoption phase, market formation and mobilization of resources were the most developed, followed by knowledge development, knowledge diffusion and entrepreneurial activity. The creation of legitimacy function was the least developed, according to the experts. In the take-off phase (2003–2012), the experts saw significant growth in all seven TIS functions compared to the decision for the early adoption phase. The market formation and mobilization of resources showed the highest development, followed by the creation of legitimacy and entrepreneurial activity. Experts felt the least-developed function in this decade was knowledge diffusion.

In the roll-back phase (2013–2022), the experts reported a decrease in the development of all seven TIS functions. Entrepreneurial activity, knowledge development, knowledge diffusion, market formation and mobilization of resources functions shrunk beyond the levels observed in the decision for the early adoption phase. The guidance for search and creation of legitimacy functions also decreased compared to the take-off phase, but still managed to survive the decline beyond the decision for early adoption phase.

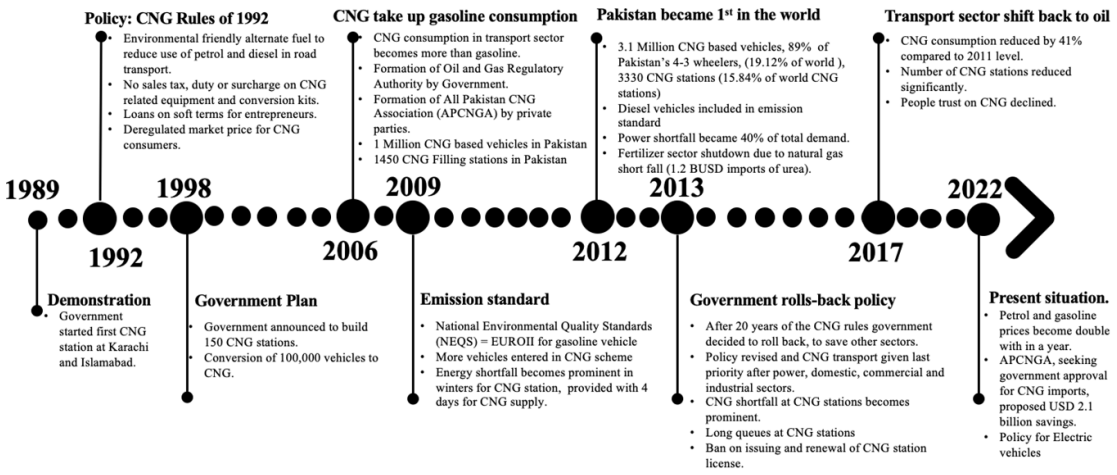

Figure 5. Evolution of the policy landscape around the CNG-based mobility system in Pakistan.

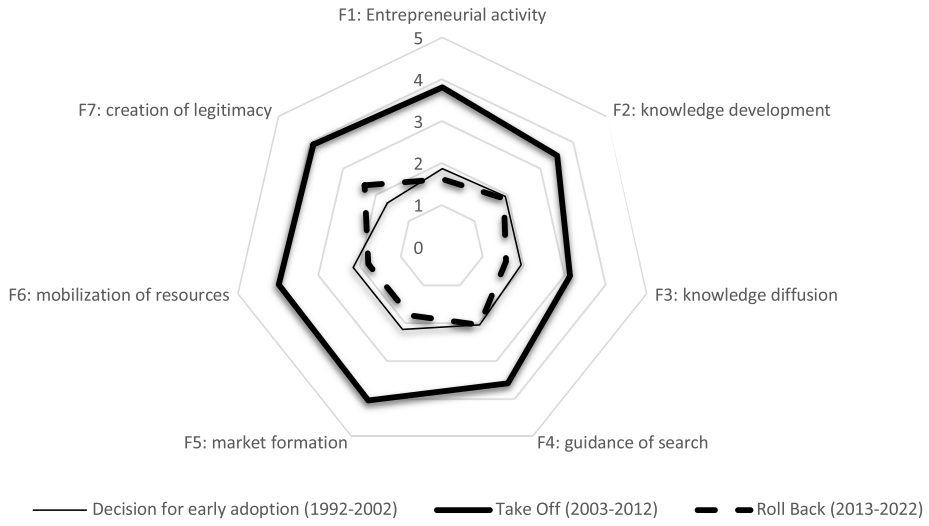

Figure 6. Step 2: evaluation of Pakistan CNG-based transport 1992–2022 TIS through expert consultation.

Step 3: Combining the results of event-based analysis and expert consultation.

When we compare (figure 7) the results from event-based analysis with those from the expert consultation analysis, the main messages are similar, which strengthens the findings from the event-based analysis.

During the decision for early adoption phase, entrepreneurial function and market formation were stronger among other functions due to favourable policies and incentives for new investors in the CNG market. However, the function of legitimacy was found to be the weakest due to the lack of knowledge development and diffusion. The absence of a consistent direction and clear vision on the part of the government also hindered the development of legitimacy. The area of the polygon (for the estimation method, see SM6) was also the smallest, showing that it is trying to gain ground to expand the process.

During the take-off phase, the area of the polygon shows the largest increase in coverage. Entrepreneurial activity was near the highest and near the boundary, with a significant increase in the number of CNG stations, investments and employment in the sector. The functions of knowledge development and market formation also improved due to standardization and training efforts by various organizations. The functions of knowledge diffusion, guidance and search, mobilization of resources, and creation of legitimacy also showed improvement but were still weaker as compared with the other functions.

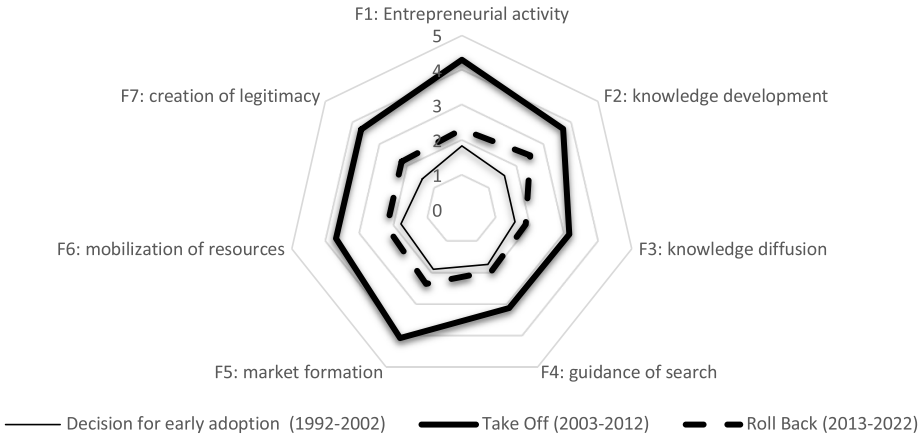

Figure 7. Result of step 3: combination of event-based analysis and expert consultation analysis.

The roll-back phase shows a shrinking coverage with smaller polygon size with a decline in the CNG-MTIS due to withdrawal of favourable policies. This decade showed a decrease in entrepreneurial activity due to a government ban on new licences and renewals for CNG stations, which discouraged new entrants and resulted in the exit of existing actors. The number of CNG stations decreased and the investments in the sector reduced, leading to a shrinkage of the CNG-MTIS compared to the take-off stage, but it did not collapse to a central point or below the decision for the early adopter stage.

The results reveal a consistent pattern in the development of all functions, with a decision for the early adoption stage followed by maturity in the take-off decade and a subsequent shrinkage in the roll-back period, as depicted in figures 4 and 6. However, expert consultations suggested that certain functions had shrunken significantly beyond the decision for the early adoption stage. Notably, the creation of legitimacy function exhibited less shrinkage in comparison to event-based analysis, which can be attributed to the recent energy crisis in the country, resulting in a price hike of 272% for petroleum products, with prices rising from Rs. 100.11/Ltr in June 2020 to Rs. 272/Ltr in March 2023 (PSO 2023). This provided an opportunity for the APCNGA to float a proposal for saving $2.1–$2.5 billion in energy imports through the revival of CNG with lignified natural gas (LNG) imports (Siddiqui 2022, Tribune 2022).

Step 4: area under the polygon for comparison of extent of transition across stages

Using the method developed to quantify the area under the polygon (for details SM1.2) specified in equation 1, we can compare the extent of transition across three stages. The estimated values are 0.35 sq. units, 30.93 sq. units, 1.29 sq. units for early adoption, take-off and roll-back respectively (table 1). The change from a smaller value to a larger value represents progress in the expansion of the transition process with improvements along the dimensions of the MTIS functions.

Table 1. Area under polygon for CNG-MTIS.

Transition stages	Emergence	Take-off	Roll-back
Area under polygon	0.35	30.93	1.29

Source: estimated by authors.

$$\text{Area under polygon} = \frac{1}{2}\left|\sum_{i=1}^{6}(x_i y_{i+1} + x_7 y_1) - \sum_{i=1}^{6}(y_i x_{i+1} + y_7 x_1)\right| \quad (1)$$

where, (x,y) are the Cartesian coordinates of a vertex of the polygon

$$x = r \times \cos\theta \text{ and } y = r \times \sin\theta.$$

r is the radius of the vertex from the origin of the polygon and θ is the angle of the vertex.

As shown in figure 8, the functions in the roll-back stage are stronger than for the decision for early adoption stage, so the area for decision for early adoption polygon is smaller than that for roll-back. Detailed results are provided in SM 6.

Step 5: Capture the blockages for the weak and enabling/highly needed functions.

The results demonstrate that all functions during the decision for the early adoption decade (1992–2002) were weaker than in the take-off decade. Nonetheless, the creation of legitimacy functions was one of the least-developed aspects, primarily due to the absence of relevant actors such as civil and environmental societies, and a lack of sufficient lobbying for CNG-based transport (for details see SM7). This is also reflected in the area under the polygon. During

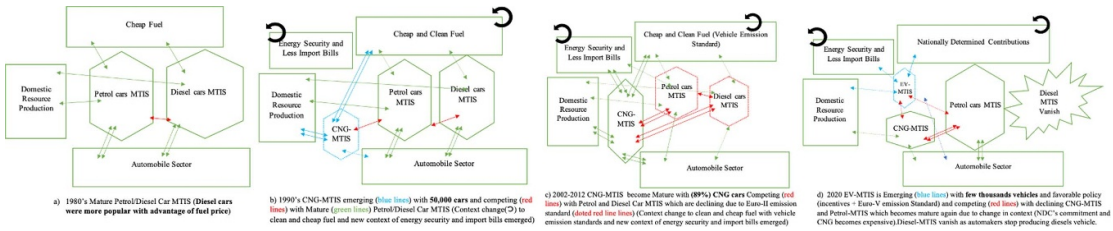

Figure 8. Pakistan transport sector parallel EV-MTIS developments and competition from external factors.

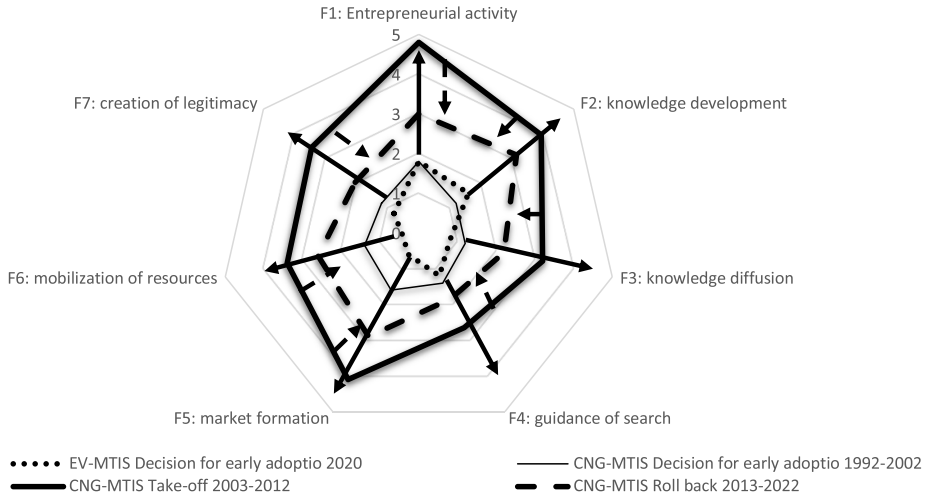

Figure 9. CNG-MTIS vis-à-vis EV-MTIS (outwards arrows represents the future expansion possibilities of EV-MTIS and inward arrows shows the contractionary policies of CNG-MTIS).

the take-off decade (2003–2012), although all functions expanded, the least-developed function was guidance and handholding support. In the roll-back phase, one of the key blocking mechanisms was the lack of clear and consistent policy support from the national government. This resulted in uncertainty, making it more challenging for organizations to make long-term investments in R&D or commercialization efforts, and slowing down the pace of technological progress. In the roll-back decade, two functions, knowledge diffusion and hand holding by policy targets and guidance, became the weakest. The imposition of a ban on CNG station licence issuance/renewal was the major blocking mechanism for all functions of the CNG-MTIS, resulting in a lack of new knowledge development and discouraging the generation of new knowledge from universities, R&D and industries, and reduced knowledge diffusion. This is a clear signal of the government's planned lack of interest in further support for the development of CNG-based transport in Pakistan. This may be due to several reasons. The most plausible seems to be a preference for the development of a parallel EV-MTIS due to landscape-level changes arising in response to national and international commitments to climate action (Butt and Singh 2023), as depicted in figure 8.

The present study depicts, taking the example of Pakistan, how the mobility sector in a developing country context is trying to respond to a series of fast-changing transitions emerging in the global landscape. As the transition to the CNG-driven mobility sector started in developing countries, global-level innovation in technology matured and made it possible for adoption by Pakistan. India also adopted CNG in many states (Patankar and Patwardhan 2017, Krelling and Badami 2021). The current roll-back phase in CNG-MTIS and the shift in focus towards electric vehicle (EV)-led transition is also policy driven (figure 9). A distinctive feature of decision for early adoption of the EV-TIS compared to the CNG-MTIS is the knowledge development function, which is more advanced in the former, as can be seen by the shapes of the respective polygons.

The entrepreneurial activities and guidance for search functions show similar scores for both CNG-MTIS and EV-MTIS. This is because, like for CNG, the government has set targets for all types of vehicles including two wheelers (which was absent in CNG-MTIS as technology was not available to make it possible towards decision for early adoption) in its EV policy (table 2). Manufacturers of e-two wheelers are emerging in Pakistan after policy implementation as

Table 2. Pakistan electric vehicle targets.

EV penetration target	Medium-term 2025	Long-term 2030	Ultimate 2040
Two- and three-wheeler	500 000	50%(900 000) of new sales	90% of new sales
Four-wheeler	100 000	30%(60 000) of new sales	90% of new sales

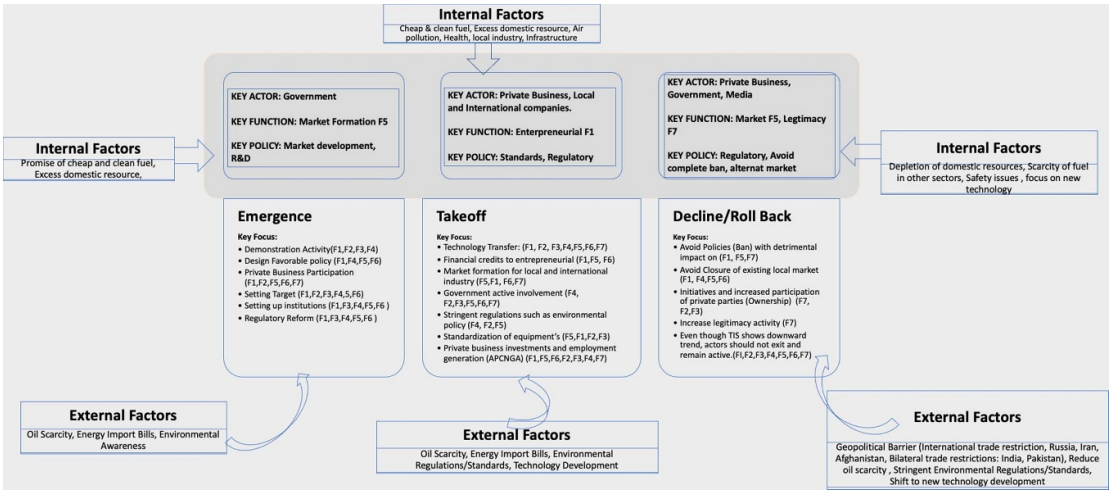

Figure 10. Priority actions/actors/functions needed for development of a successful TIS for new emerging technologies.

technology matures. Entrepreneurial activities characterized by technology manufacture and installation, as well as the entry of new firms such as Vlektra and Jolta Electric in the two-wheeler market, Sazgar in the three-wheeler market, and MG motors and Nur in the four-wheeler market, respectively, are similar to before. On the other hand, the knowledge development score is higher for EV-MTIS. A Scopus search of peer-reviewed articles using the keywords 'Electric Vehicle' and 'Pakistan' yielded 47 articles, 41 of which were published in the last 5 years (2019–2023). Furthermore, the search guidance for EVs is better, as the government has set more aggressive targets for all types of vehicles in its EV policy (table 2), in contrast to CNG which was initially introduced for four-wheeler passenger vehicles and three-wheelers and later encouraged for public transport and buses. However, the market formation and mobilization of resource functions of the EV MTIS are less developed, possibly due to Pakistan's recent economic crisis, which resulted in import bans (including EVs), energy crises and power shortfalls (Zamir and Yep 2022, Shah 2023).

The areas under the polygon for the decision for early adoption stage (event-based) for CNG-MTIS (1992–2002) and EV-MTIS (2020–2023) are 2.55 sq. units and 0.84 sq. units, respectively. It needs to be noted that CNG-MTIS is shown for one decade while for EV-MTIS it is only for 2.5 years. Progress is evident in all functions except for knowledge development. This can be due to the high upfront cost and ongoing negative discourse on awareness and safety issues with EVs (Halsnæs *et al* 2023). Moreover, CNG-MTIS, although facing roll-back, has not yet collapsed and could create a market barrier. The CNG-MTIS market expansion from the very beginning facilitated a faster push to the take-off stage through the entry of many actors into the market.

Step 6: policy, priority actions and actors necessary for enabling functions of the MTIS

In summary, as shown in figure 10, the CNG-MTIS results show that during the decision for early adoption phase, priority actions should focus on demonstrating new technologies and implementing policies that support market formation and entrepreneurial activities. In contrast, the take-off phase requires actions such as more stringent emissions standards for competing fuels, promoting national and international collaboration, facilitating investment, and standardizing and certifying supply chains (e.g. it was for CNG kits and cylinders). However, the roll-back phase involves imposing bans on various activities, including renewal and issuance of CNG station licences, public transport and new manufacturing units, which could negatively impact the TIS by hindering entrepreneurial and market formation. Policymakers need to weigh the costs and benefits of such actions and identify alternative strategies to achieve their goals while minimizing negative impacts on the MTIS. SM8 provides a detailed list of priority actions and their impacts (direct and indirect) on MTIS functions to promote the development of the MTIS during each

phase along with key actors and major policy focus recommendations.

4. Discussion

Pakistan's case study shows that once the decision for early adoption of CNG technology was taken, entrepreneurial functions and market formations were driven by the CNG Production and Marketing Rules 1992, a policy for easy loans, and the removal of tax and import duties (Khan and Yasmin 2014). Developing countries are trying to follow the international low-carbon transition path and sometimes lack incentive to create national legitimacy functions in the absence of long-term visions (Bergek *et al* 2008, Wieczorek 2014). The government's obligation to convert all government vehicles to CNG (NGV Global 2006) played a significant role in initiating the process.

The lack of long-term vision through creation of legitimacy clearly was reflected in the roll-back period (2013–2022) of CNG. It may also be interpreted as a deliberate decision by policy makers to take early mover's advantage in the global electromobility trend at a time when there is growing resource depletion pressure on domestic CNG sources, which triggered the need for a planned roll-back without leaving it to unmanaged social struggle. One can argue that, in the later years of the third decade, CNG policies, although perceived as inconsistent for further growth of CNG, align with the government's goal of reducing use of CNG in the transport sector given the declining supply of domestic CNG. Despite the active presence and maturity of all actors involved in entrepreneurial activity, the government's announcement to roll back the CNG-based transport policy due to scarcity of natural gas resources (Government of Pakistan 2013, Boone 2013) became a dominant driver. While parallel policies encouraging natural gas use for the domestic, industrial, power and fertilizer sectors started creating new dynamics in these sectors, momentum was lost in the transport sector. The government's policy of imposing a ban on new licence issuance for vehicles and renewal for CNG stations for transport fuel resulted in the exit of existing actors, both national and international, and discouraged new entrepreneurs from entering the mobility sector CNG-related business. As a result, the number of CNG stations declined from around 4000 to 1958 from 2011 to 2020 (OGRA 2021). The news media began reporting negative events, such as a decrease in the number of stations, CNG crises and accidents, and bans on multinational companies such as Landi Renzo, which created a barrier to growth (Ahmad *et al* 2014, Bhutta 2014, Crisis24 2021, OGRA 2021, Republic World 2021, Siddiqui 2021).

Comparative analysis of Pakistan's CNG-MTIS (1992–2022) and the Netherlands's ANG-TIS (1970–2007) (for details see SM9) shows some interesting contrasts. As leaders in innovation, the impetus for innovation in ANG-TIS was driven by entrepreneurial activity during its emergence (1970–1989) (Suurs *et al* 2010) in Pakistan. As a follower of market-ready innovations, the expansion of the market was driven by government-led policy. It is a good example for developing countries of how the widescale favourable policy innovations in Pakistan have created public acceptance and trust, leading to an influx of new entrepreneurs into the CNG business. The clear price advantage of CNG (50% cheaper than gasoline and diesel) encouraged its adoption by new users. The decision for the early adoption phase of the CNG-MTIS in Pakistan and the emergence followed by the early adoption phases in the ANG-TIS in the Netherlands had different sets of key actors, for obvious reasons (see figure 11). The emergence of the ANG-TIS in the Netherlands through innovation was driven more by EU environmental issues and oil scarcity, while in Pakistan it was more driven by domestic factors, an abundance of domestic natural gas reserves as cheap, clean alternate fuels for the transport sector when the need for low carbon development was rising, new CNG-based technology, and mature infrastructure. Agents of change for the Netherlands were entrepreneurs, whereas in Pakistan, it was the government playing the dual roles of decision-maker and policy-maker for market formation, as shown in figure 11.

In the second decade of take-off (2003–2012), it was again a government institution, in collaboration with other actors such as the APCNGA, that boosted entrepreneurial activities, facilitated market formation and promoted knowledge development. These drove all other functions of the CNG-MTIS. Hence, entrepreneurial activities can be identified as the driving force behind innovation in the take-off decade. In contrast, the take-off period of the Netherlands ANG-TIS between 2005 and 2007 was driven by market formation and search guidance. After a decline between 1990 and 1999 and re-emergence between 2000 and 2004, the entry of new actors, such as municipalities and provincial governments, air quality standards regulations, local market development, financial incentives, and oil scarcity, boosted the ANG-TIS. The agent of change for the Netherlands's take-off was market formation, while in Pakistan, it was entrepreneurs (Suurs and Hekkert 2009) as shown in figure 11.

The roll-back (2013–2022) of the Pakistan CNG-MTIS was forced by domestic resource scarcity while in the Netherlands ANG-TIS (1990–1999), roll-back was forced by liberalization of gas companies (Suurs and Hekkert 2009), as shown in figure 11. In both

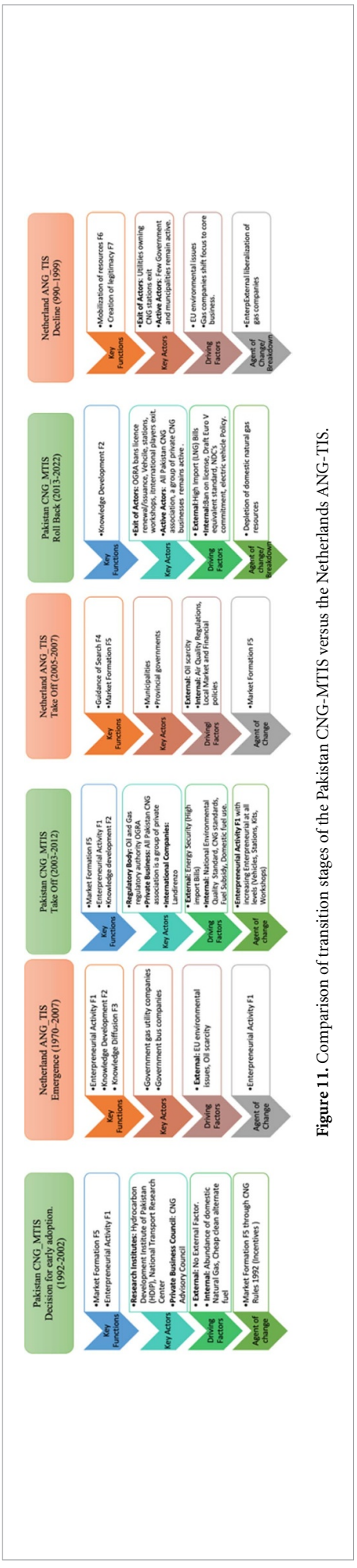

Figure 11. Comparison of transition stages of the Pakistan CNG-MTIS versus the Netherlands ANG-TIS.

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countries, changes in the gas sector led to roll-back. While in Pakistan a depleting domestic gas supply led policy makers to roll-back, in the Netherlands gas companies in a deregulated market moved back to concentrate on their primary business. For instance, after merging with the energy provider Nuon, ENW, which owned a major portion of the existing ANG refuelling infrastructure, gave up on the plan and sought to sell their refuelling stations in Velsen, Haarlem, Alkmaar and Amsterdam. Project cancellations resulted in the exit of actors and gave ANG technology a bad reputation among future users.

5. Conclusion

This study is intended to show how, on a global zero carbon transition path, developing countries as latecomers in the innovation chain can accelerate transformative change through government decisions for early adoption of new mature technologies. The example that has been used here is from the mobility sector in Pakistan, but is applicable to developing countries as they are as a group negotiating for technology transfer and adoption to shift development in the near term on a sustainable development trajectory (Lecocq *et al* 2022, IPCC 2023). Examining the revised NDCs of various developing countries (Government of Thailand 2022, Government of India 2022, Government of Pakistan 2021, Government of Pakistan 2021, Government of Bangladesh 2021) reveals common elements, such as a focus on technology transfer and adoption (SM 1.1). Specifically, there is a shared emphasis on designing incentive mechanisms in the form of international finance to support technical assistance and technology transfer funds for purchasing intellectual property rights for free distribution of clean technologies to accelerate decarbonization.

The application of the modified TIS framework is customized to represent the technology adoption and leapfrog characteristics of developing countries, as technology followers, where long innovation chains can be avoided. The analysis of the CNG-MTIS in Pakistan shows that, in developing countries, policy-driven low carbon transition management is possible and policy can be a major enabler even if cascading transitions need to be managed. Government policy changes can enable several functions in a multidimensional transition process. This can be achieved by establishing appropriate context-specific incentives for market expansion, entrepreneurial activity, knowledge processing, development and dissemination, resource mobilization, and legitimacy. Institutional support or advocacy through civil society engagement agencies can provide directionality and influence the transition process expansion in a time-bound manner. The decision for early adoption need not only be in one sector, it can be in multiple sectors depending on national needs and priorities and would need coordinated actions with a variety of social actors, thus creating a movement within society.

The roll-back phase of CNG in Pakistan is a good example that demonstrates how policies can be managed in the face of cascading innovations to welcome a new superior innovation. The case here is electromobility, by rolling back the preceding transition. However, it also illustrates that when the period for roll-back aligns with new emergence, improved articulation can mitigate social struggles. During the third decade (2013–2022) of the CNG-MTIS, unlike the decision for early adoption stage (1992–2002), it seems that in the roll-back stage there was less prior planning, and thus articulation from the government led to social struggle. Our findings show that the drastic withdrawal of policy support in very short time without prior articulation or consultation with the CNG sector supply chain left the latter with uncertainty in terms of business outcome and the CNG infrastructure in which they invested, which are becoming stranded assets. This contributed to confusion in the market expansion of EV-MTIS functions, as trust in policy was undermined. Good policy practices from the CNG-MTIS could be used to facilitate a smooth EV transition. However, the situation with the latter has one more layer of complication that needs to be realized and incorporated into policy framworks. The EV-MTIS in stage 1 needs a smooth policy-driven roll-back of the CNG-MTIS through planned articulation to maintain investors' support and trust in policy. By implementing properly planned retraining processes and compensation mechanisms, CNG-MTIS investors could smoothly transition into the market expansion process of the EV-MTIS, which could be a win–win outcome. In the ANG-TIS in the Netherlands, gas companies involved in transport sector infrastructure development had the flexibility to swiftly revert to their original gas business. In Pakistan and many developing countries, there is a need for supportive guidance for managing cascading transitions. However, instead of managing this transition with broader societal change, driven by national and international commitments, the government is focusing on pushing EV technology as a clean and economical fuel (Engineering Development Board 2020, Shakeel 2022, Butt and Singh 2023). It needs to be recognized that the CNG-MTIS came with many win–win options and positive enabling factors. The introduction of new activities, new infrastructure, new business opportunities and jobs created optimism within the economy, which generated social acceptance. However, the emergence of EV has surprised incumbents and causing disruptions among certain segments of society, which has not been adequately explored in recent literature (Butt and Singh 2023). Therefore, focusing only on consumer need fails to address the just transition issue and could delay the process. The same is

true for many developing countries as they all will need to face the challenge of cascading transitions. For example, India, Bangladesh and Thailand, who recently adopted EV policies, share similarities with Pakistan in terms of their vehicle markets. In India, two-wheelers constitute 75% of the total vehicle fleet, while in Thailand, they make up approximately 60% and in Bangladesh, the figure is around 80%. They also have CNG vehicles that were introduced around a similar time period through policy interventions and now moving towards EV. It is necessary to consider the inclusion of individuals or entities adversely affected within the CNG-MTIS framework. Targeted measures such as reskilling, retraining, redirection of finance, compensation for stranded assets and rehabilitation for losers in the newly emerging system could restore trust in policy. This, in turn, can facilitate a sustainable fast transition towards long-term transformation through the EV-MTIS. Therefore, TIS dynamics management, especially in a complex situation where roll-back of one is cascading/overlapping with emergence of another new technology, can be handled through a just transition framework and managed with limited social struggle. While CNG technology has historically dominated the market for four-wheeler and three-wheeler passenger cars in Pakistan, due to the entry of local manufacturers like Jolta Electric, MS Group and Vlecktra (Talal 2022), EV penetration in these markets needs special attention. The number of e-two wheelers is 18 000 and there are 2000 e-cars (Jamal 2023). EVs have made headway in the two-wheeler category, a segment not covered by the CNG-MTIS, and make up around 82% of Pakistan's passenger transportation (Pakistan Bureau of Statistics 2022). This aspect could contribute to a smoother transition in the near term.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Accelerating Actions for Leveraging a Climate-Neutral, Sustainable Society

Energy sector sustainability for a fast-growing economy like Bangladesh: an empirical assessment

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Abstract

Fast-growing economies like Bangladesh are expected to experience high growth in GDP, and in energy use with structural shifts towards digitalization and industrialization in the coming decades. However, given the goal of global net zero carbon growth, energy sector development will need to satisfy multiple sustainability criteria simultaneously. This paper examines empirically the trends in sustainability indicators for Bangladesh's energy sector to assess the current status based on past trend. A long list of 438 indicators is compiled from the literature used in various country contexts for understanding energy sector sustainability but this study identifies a short list of 38 Bangladesh-specific indicators and develops a composite index. Principal Component Analysis (PCA) method was used for weighting individual indicators to arrive at the composite index. Results show that Bangladesh is showing marginal progress towards sustainability of the energy sector. While progress in social and economic indicators such as increasing access to cleaner fuel, electrification, productive use of energy, increased diversity of fuel mix has aided in advancing sustainability, the deteriorating environmental indicators over time is pulling down the sustainability status of the energy sector. Among other things, increasing share of fossil fuel in energy mix, lack of adequate improvement in energy efficiency in all sectors, increase in methane emissions need attention and solution to make energy sector sustainable. These steps can also help in reducing overall energy demand and emissions without adversely impacting social and economic growth through deployment of appropriate fuel choice, technologies and infrastructure. For better monitoring of energy sector sustainability, some data gaps for Bangladesh have also been identified.

Keywords Sustainable development goals · Sustainable energy sector · Energy demand · Developing countries · Composite sustainability index

Introduction

Fast-growing economy is defined here as one which is experiencing an annual Gross Domestic Product (GDP) growth rate of 7–10% over a period of time (Mahmud 2021; Mahmud and Roy 2020; Saravanan et al. 2011). A country born

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in 1971, Bangladesh as a late comer in the economic growth process, attained 8% GDP growth rate in 2019 and became one of the fastest-growing economies of this century in the region (WB 2020b). Bangladesh for its economic growth will need more energy and, thus, opens up enormous opportunities to avoid unsustainable high carbon trajectory lock-in by making right choices for energy sector infrastructure at this stage of development (Goldstein et al. 2023; IPCC 2022; Vergragt et al. 2011).

Historically, the fast-growing phases of China (1978–2009), Singapore (1966–1990), Malaysia (1961–1997), and South Korea (1966–1990) were driven primarily by fossil fuel-dependent heavy industrialization process for economic growth. Although each country started with agricultural modernization and import substitution, agricultural sector's relative contribution reduced eventually. The rapid economic boom was driven by export-oriented labor-intensive industries but later got substituted by capital-intensive heavy industries. In the next phase, service sector or light modern high-tech industries contributed the most (Roy et al. 2021).

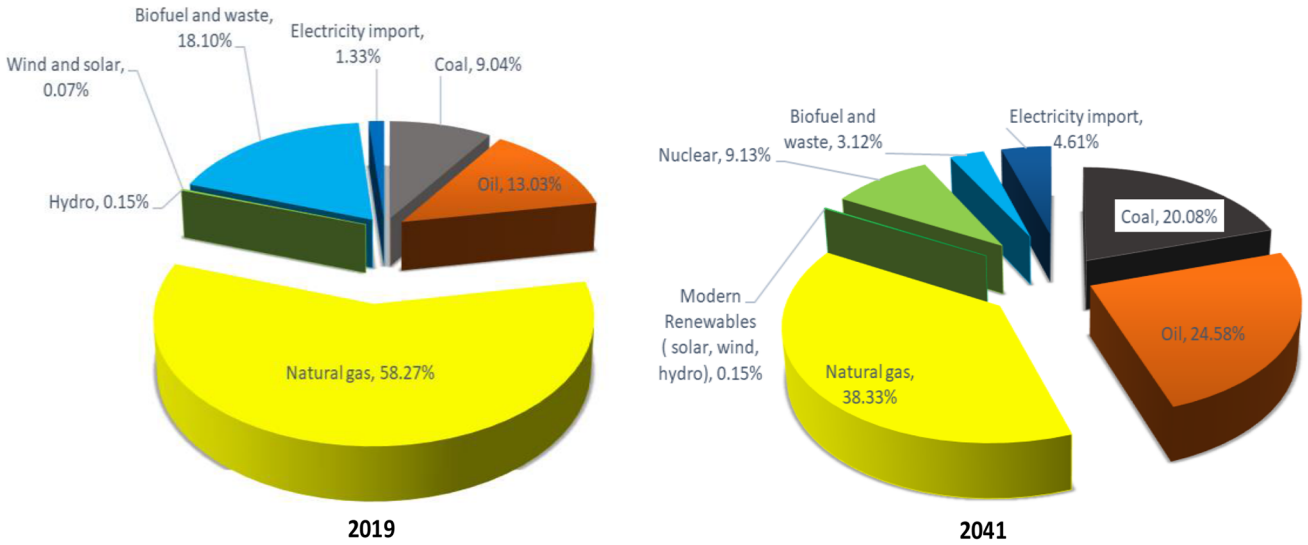
After political independence in 1971, Bangladesh advanced through agricultural modernization, and gradually shifted from agro-based to non-agricultural manufacturing industry-based economic structure (Bangladesh Bureau of Statistics 2018; Mahmud et al. 2017; WB 2020a). Bangladesh for maintaining fast economic growth is planning for capital-intensive heavy industries by embracing global digitalization trend (Burlamaqui and Kattel 2014). Energy is inextricably linked to the growth of heavy industries and in digitalization process. Energy and industry sectors continue to be the world's greatest emitter of greenhouse gases (IPCC 2022). Cheap fossil fuel-driven economic expansion in the four Asian countries in the last century is not replicable for Bangladesh (Mahmud and Roy 2020). Clean renewable energy sources are becoming increasingly affordable (IPCC 2022; Mahmud and Roy 2021). In the case of Bangladesh, 75% of its energy supply infrastructure will be created over the next 2/3 decades to sustain the country's rapid economic expansion. As a result, the country is in a much better position than other fast-growing Asian countries of the past century because for Bangladesh the future 100% of energy sector infrastructure is not already locked-in on a fossil fuel path. It can take advantage of global market development trends in the energy sector to develop new sustainable domestic energy system (Roy and Mahmud 2021; Roy et al. 2020).

In this backdrop, understanding the current status of sustainability of the energy sector for Bangladesh, its strong and weak points can help in formulating actions for achieving 2030 SDGs and 2041 national goals keeping in view the country's long-term delta plan (GED 2018, 2020; Katekar et al. 2020). What criteria should one take for assessing sustainability of energy sector of Bangladesh? There are literature (Hannan et al. 2018; Rösch et al. 2017; Shaaban and Scheffran 2017; Sharma and Balachandra 2015; Xu and Song 2018) which assessed sustainability of energy sector in other country contexts. As a starting point, one can review and identify indicators which can be adopted and customized in assessing sustainability of energy sector for Bangladesh. In the literature and in global assessment, it is now well established that different countries are at different stages of development and development stage-wise sustainable development priorities will vary (IPCC 2022, 2023). Energy sector and its sustainability challenges are country context specific. So, refined country-specific indicator set will provide a better tool for assessment. The specific objectives of this paper are to (a) create a comprehensive indicator library for assessing the sustainable development of the energy sector general, (b) identify the indicators relevant for assessing Bangladesh energy sector sustainability, and (c) apply an indicator-based hierarchical multi-dimensional framework to evaluate, compare, and benchmark the Bangladesh energy system towards sustainability. There is no available comprehensive empirical study on Bangladesh that evaluates using national data the energy sector's sustainability status to guide national policy and actions. This study seeks to bridge that gap by identifying Bangladesh-specific indicators and by estimating composite index using available data that can help in evaluating the aggregate energy sector sustainability status for Bangladesh. Novelty of this paper needs to be understood in the light of country-specific knowledge gap. Use of empirical evidence and comprehensive assessment for energy sector sustainability for Bangladesh is the contribution of this study which has policy relevance and can be compared to other country studies. In "Materials and methods", we present the materials and methods, followed by results and discussions in "Results and discussion" and conclusions in "Conclusions".

Materials and methods

Energy supply sector in Bangladesh currently is heavily reliant on fossil fuels. Figure 1 depicts the country's less diversified energy supply mix in 2019. It demonstrates that natural gas is the primary energy source of energy in Bangladesh, accounting for 58% of the total energy supply, while renewable energy sources such as solar, wind, and hydro accounts for only 0.22%.

Domestically available natural gas is the dominant primary fuel source, but the domestic reserves are projected to deplete in near future in the absence of new discoveries (Hetol et al. 2019). With depleting natural gas, Bangladesh government decided in 2018 to import Liquified Natural Gas (LNG), which accounts for 11% of natural gas supply in



Data Source: (Bangladesh Power Division, 2016; IEA, 2020)

Fig. 1 Energy supply mix in Bangladesh, 2019 and 2041

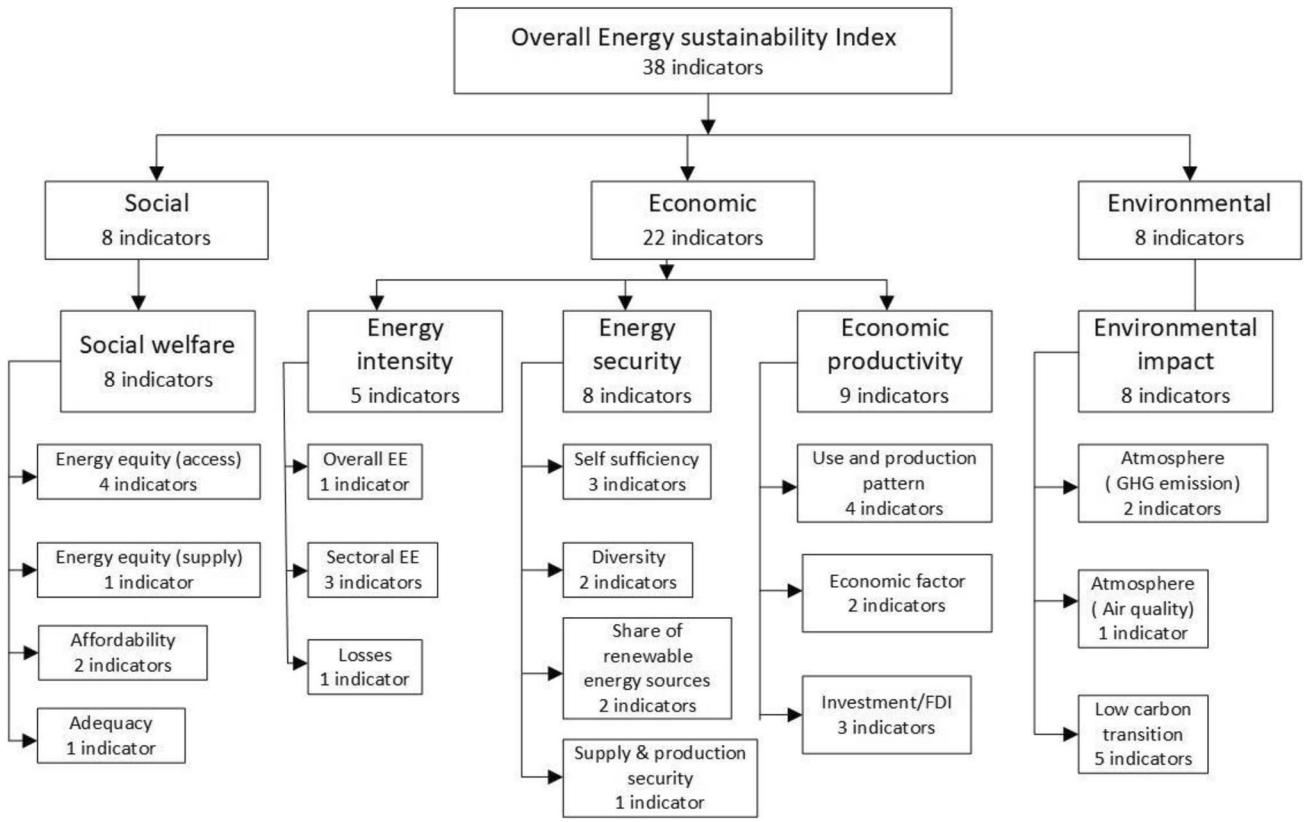


Fig. 2 Sustainability dimensions, themes, and sub-themes in multi-dimensional hierarchical framework for assessing sustainability of Bangladesh energy sector

2018 (Hydro Carbon Unit 2020) and also gradually increase coal share. The country started importing energy from neighboring countries in 2014 and domestically generating electricity via grid-connected solar photovoltaic (PV) in 2017 (Chowdhury 2020). The first nuclear power plant, with a capacity of 2400 MW, will be operational by 2024 (Rooppur NPP Project 2019). Although the 2016 PSMP excludes renewables, the government recently announced the cancelation of ten major coal power projects out of 18 planned, with the aim of producing 40% of energy from renewables by 2041 (Roy 2021).

We adopt from the literature (Romero and Linares 2014) for defining sustainable development of the energy sector, shown in the hierarchical framework (Fig. 2) all three broad dimensions of sustainable development: social, environmental, and economic for the empirical assessment of Bangladesh energy sector sustainability. While defining the sustainable development of the energy sector under three main dimensions, several studies mention some common themes/elements (Table 1) which we integrate with sustainable development dimensions (Fig. 2). It is also important to note that energy sustainability themes are country specific. Some issues like the affordability of the poor people or energy access to more people are important for the developing and least developed countries. In contrast, in the country that already has achieved universal access, priority goes to the more use of renewables, ensuring environmental sustainability (Shortall and Davidsdottir 2017; Vezzoli et al. 2018). Therefore, we accept that sustainable development of the energy sector for Bangladesh can be represented broadly under five representative themes: social welfare, energy intensity, energy security, economic productivity, and environmental impact which can further be disaggregated or represented by various sub-themes (Fig. 2). The respective themes and sub-themes are in the third and fourth levels in the hierarchy. We compiled based on literature review a long list of indicators used in various country contexts for understanding energy sector sustainability. Selection process of the final short list of Bangladesh-specific indicators under sub-themes is mentioned in Sect. "Composite energy sector sustainability index for Bangladesh" and specifically in Sect. "Preparation of short list of indicators" below. These indicators constitute the lowest level in the hierarchy (Fig. 2).

Past studies: energy sector sustainability assessment

Multidimensional approach to assess sustainability of energy sector is a complex issue. The most widely accepted way of tracking this multi-dimensional assessment is the selection of appropriate indicator/s and construction of an index (Mccool and Stankey 2004). A properly designed set of indicators transforms the basic statistical information to provide a deeper understanding of the system, including its inter-linkages and trade-offs (Vera and Langlois 2007). For assessing energy sector sustainability, dimension-specific indicator set should be selected to capture information of the energy situation relevant for variety of stakeholders (Mainali et al. 2014; Patlitzianas et al. 2008; Shortall and Davidsdottir 2017; Vera and Langlois 2007). Multinational organizations (IAEA et al. 2005; World Economic Forum 2015) identified indicator set and estimated composite index to assess energy sustainability. The well-known Energy Indicators (a

Table 1 Key elements for sustainable development of energy sector

SL	Key elements /themes	List of references
1	Improved energy efficiency	Brundtland (1987), IAEA et al. (2005), Iddrisu and Bhattacharyya (2015), Neves and Leal (2010), Rosen (2009), Santoyo-Castelazo and Azapagic (2014), Shortall and Davidsdottir (2017), Tester et al. (2012), Un General Assembly (2015) and UNDP (2000)
2	Social welfare	Fathurrahman (2016), IAEA et al. (2005), Iddrisu and Bhattacharyya (2015), Neves and Leal (2010), Santoyo-Castelazo and Azapagic (2014), Sharma and Balachandra (2015), Shortall and Davidsdottir (2017), Tester et al. (2012) UN (2015), UNDP (2000) and World Energy Council (2018)
3	Energy security	Fathurrahman (2016), IAEA et al. (2005), Iddrisu and Bhattacharyya (2015), Neves and Leal (2010), Rosen (2009), Santoyo-Castelazo and Azapagic (2014), Sharma and Balachandra (2015), Shortall and Davidsdottir (2017), Tester et al. (2012), UN (2015), UNDP (2000) and World Energy Council (2018)
4	Economic feasibility	Brundtland (1987), Golušin et al. (2013), IAEA et al. (2005), Iddrisu and Bhattacharyya (2015), Neves and Leal (2010), Sharma and Balachandra (2015), Shortall and Davidsdottir (2017), UNDP (2000) and World Energy Council (2018)
5	Minimizing environmental Impact	Brundtland (1987), Fathurrahman (2016), Golušin et al. (2013), IAEA et al. (2005), Iddrisu and Bhattacharyya (2015), Neves and Leal (2010), Rosen (2009), Santoyo-Castelazo and Azapagic (2014), Sharma and Balachandra (2015), Shortall and Davidsdottir (2017), Tester et al. (2012), UNDP (2000), and World Energy Council (2018)

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collection of 30 indicators) for Sustainable Development (EISD) developed by International Atomic Energy Agency (IAEA), have been widely used to assess energy sector sustainable development (Angelis-Dimakis et al. 2012; Martchamadol and Kumar 2013; Weber and Martinsen 2013), but some of these indicators are too broad to be measured in specific country context (Ugwu and Haupt 2007). Since 2010, the World Energy Trilemma Index (ETI) is published annually by the World Energy Council (WEC) to present the assessment of energy sustainability at the national level, using the common set of 31 indicators for each country (World Energy Council 2021). The World Economic Forum, on the other hand, has produced the Energy Architecture Performance Index (EAPI) since 2013 to evaluate the energy systems of 127 nations using a set of 18 common indicators (World Economic Forum 2015). The reliability and validity of WEC and WEF indices are questioned due to a lack of methodological openness (Shortall and Davidsdottir 2017). However, they offer decision-makers with valuable suggestions for developing their own national sustainability assessment tool for the energy sector (Shortall and Davidsdottir 2017). Iddrisu and Bhattacharyya (2015) proposed a composite multi-dimensional index that can be used to assess sustainable energy development using very simple data and measure sustainability index for 61 nations, including Bangladesh. However, it was released in 2015, before the SDGs were agreed upon internationally. They utilize 12 indicators that represent characteristics of several nations and are unable to capture country-specific issues. Agovino et al. (2017) constructed a composite index tool to examine national energy sustainability routes of 136 countries worldwide using a common set of 38 indicators. Armin Razmjoo et al. (2019) proposed new indicators and indices in a seven-dimensional framework for 12 different countries to estimate energy sustainability. But the country or region-specific issues cannot be captured by the common set of indicators used in the above global level studies. Thus, it is necessary to build a sustainability assessment tool to analyze the energy sector development for the individual countries to capture country-specific sustainable energy sector issues. García-Álvarez et al. (2016) created a composite index to examine the EU member states' energy sustainability, focusing on energy supply, market, and environmental aspects. A total of 33 indicators were selected from the IAEA indicators (IAEA et al. 2005). Mainali et al. (2014) used 13 indicators to assess the development of rural household energy sustainability in six countries: China, India, South Africa, Ghana, Sri Lanka, and Bangladesh. Fathurrahman (2016) created an indicator-based sustainability monitoring system to track the growth of the energy sector for 15 emerging economies, including Bangladesh, with an emphasis on sustainable energy performance and renewable energy development. The Principal Component Analysis method was used to get the final list of 14 indicators. Several researchers attempted to find specific indicator sets that accurately reflect the respective nation context of energy sustainability while incorporating country-specific issues. Some of the researchers (Rösch et al. 2017, 2018; Schlör et al. 2013, 2018) evaluated the sustainability status of German energy sector concurrently, but their methodologies and emphasis varied. Xu and Song (2018) developed an indicator set and methodology for a composite index to assess China's energy sector's sustainability.

Sharma and Balachandra (2015) investigated the Indian electrical system's sustainability using an indicator-based multi-dimensional framework approach. The authors then examined if sustainable transitions can occur in the Indian electrical system in the future, up to 2031, using 29 indicators associated with sustainability transitions from their initial 85 indicators selection (Sharma and Balachandra 2018). Akber et al. (2017) developed indices to assess the life cycle sustainability of power generating technologies in Pakistan. They used twenty indicators selected after conducting a literature review, considering local applicability, and brainstorming. Khan (2019) used Multi-Criteria Decision Analysis (MCDA) to examine the past and future sustainability of power generation technologies in Bangladesh and to generate technology-specific sustainability indices. A total of 19 indicators were chosen for the indices based on their prevalence in the literature, local application, and expert consultation.

Each country has its own climatic, political, social, economic, and technical conditions that affect energy decisions (Gralla et al. 2017). Considering the case of developed nations, the sustainability seeks to address environmental concern; while, in case of developing nations, the issues related to society like prosperity and poverty get priority in assessing the sustainability of energy system development (Muhumuza et al. 2018; Sarkar 2010). The above review shows that indicator approach is a widely accepted empirical method for accessing sustainability of the energy sector in various national contexts. Researchers urge to incorporate country-specific issues rather than using common set of indicators. Some such national studies are for Germany (Rösch et al. 2017), for China (Xu and Song 2018) and for India (Sharma and Balachandra 2015) to derive policy recommendations.

Composite energy sector sustainability index for Bangladesh

Figure 3 narrates the steps followed in construction of energy sector sustainability index for Bangladesh. To select appropriate indicators for sustainable development of the energy sector in Bangladesh, we use a systematic procedure. Based on the literature review, an ‘indicators library’ is prepared

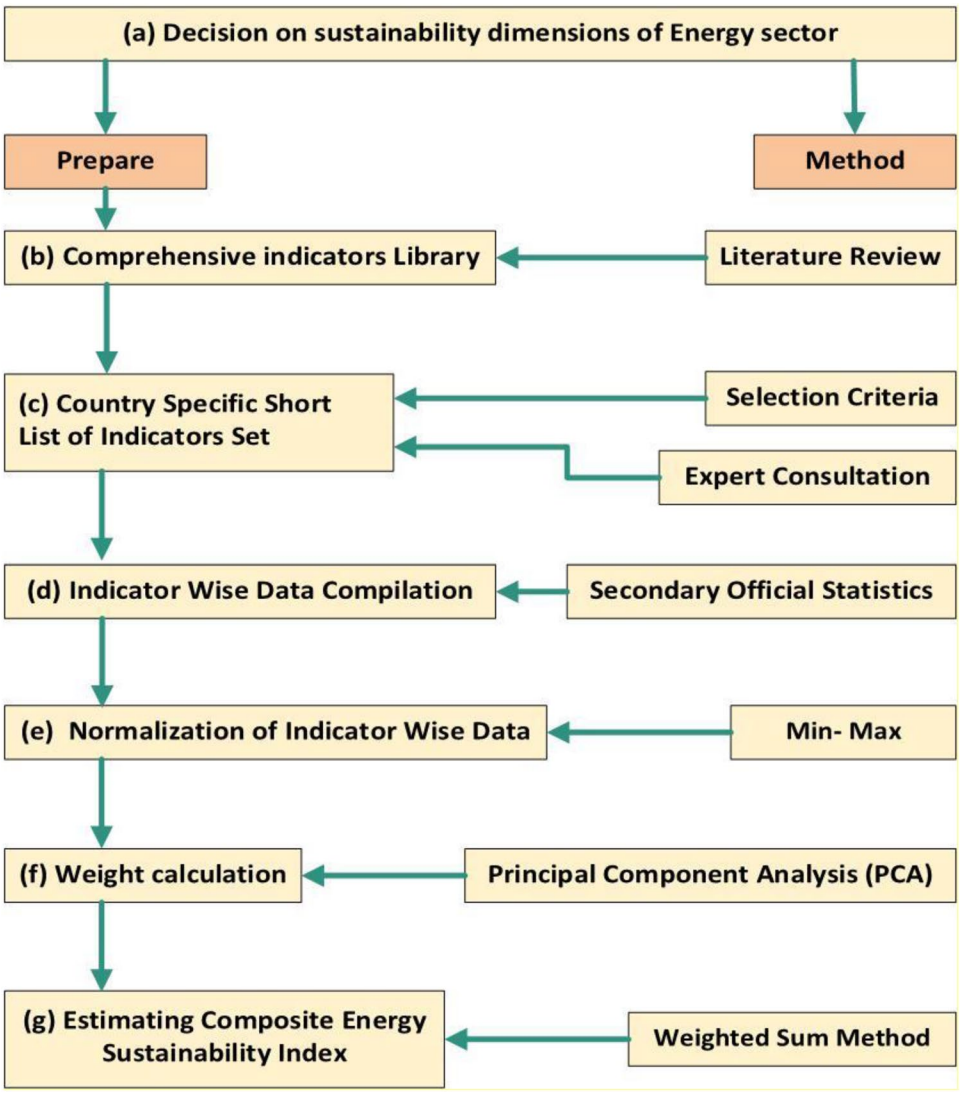

Fig. 3 Steps to construct composite sustainability index for energy sector

with a long list of indicators. The list is subsequently refined to represent country-specific short list of indicators.

Compilation of an indicator library: long list of indicators

We first listed all the indicators so far used in various literature applied in diverse country contexts and we ended up compiling a long list of 438 indicators used by many researchers, mostly during 2015 and 2019. This list is provided in the Supplementary Material 1 (SM1).

Preparation of short list of indicators

It is overwhelming or unrealistic to track progress or to obtain meaningful insight from such a huge number of indicators (Iddrisu and Bhattacharyya 2015) as identified in Sect. "Compilation of an indicator library: long list of indicators" (SM1). It is clear that it is not necessary to deal with all these 438 indicators in the context of Bangladesh.

The criteria we adopted for preparation of the shortlist of indicators are given in Table 2 in order of preference. Using the selection criteria, data availability validated through expert consultation (Table 2), we selected, merged, and modified wherever necessary to finally prepare a shortlist of 38 indicators: 8 social, 22 economic, and 8 environmental indicators. The group of experts from Bangladesh consulted include technical and non-technical policy makers, researchers in the field of sustainable development, climate change, and economics (for more details please see) (Mahmud and Roy 2021). For Bangladesh which of the indicators (in SM1) satisfy these seven criteria (Table 2) is shown in Supplementary material (SM1) table using the symbol "$\surd$". If an indicator fails to meet a criterion, it is marked using the symbol "×" and is not included in the final list. Once an indicator is

Table 2 Selection criteria for refining the long list of indicators

SL	Criteria	Meaning	References
1	Relevance/ consistency with objective/ goal	Ability to explain energy sector sustainable development for a fast-growing economy such as Bangladesh, connection with SDG 7	Fathurrahman (2016), Grafakos et al. (2016), Liu (2014), Liu et al. (2018), Mainali et al. (2014), OECD (2008), Rösch et al. (2017), Santika et al. (2019), Shaaban and Scheffran (2017), Singh et al. (2009) and World Energy Council (2018)
2	Data availability	Availability of country-level data for the chosen Indicator for Bangladesh	Grafakos et al. (2016), Gralla et al. (2017), OECD (2008), Rösch et al. (2017), Sharma and Balachandra (2015), Singh et al. (2009) and World Energy Council (2018)
3	Non-Redundant	Indicators should not be repetitive. Every Indicator should be unique to represent the specific information	Grafakos et al. (2016)
4	Dynamicity	Capability of an indicator to capture the ongoing dynamic process of sustainable energy sector development. The indicator should represent past, present, and future trends in the sustainable energy system	Liu et al. (2018)
5	Measurability	Quantifiable	Gralla et al. (2017), Liu (2014), Mainali et al. (2014), OECD (2008), Shaaban and Scheffran (2017) and Wang et al. (2009)
6	Simplicity/ understandable	Understandable to users and practically applicable without any difficulty	Rovere et al. (2010), Shaaban and Scheffran (2017) and Singh et al. (2009)
7	Sensitivity	Capable of analyzing the trends	Grafakos et al. (2016), Rovere et al. (2010), Shaaban and Scheffran (2017) and Singh et al. (2009)

Source: Compiled by the Author

marked "×" against any single criteria, it is not considered in the selection process.

First, 296 indicators were chosen based on "relevance" criteria from the library of 438 indicators compiled through literature review. Then, 296 indicators were screened against "data availability" criteria and 199 indicators were selected at this stage. Following that, we applied "non-redundant" criteria and 44 indicators passed this stage. Subsequently, remaining four criteria: dynamicity, measurability, understandability, and sensitivity were applied, and finally we arrived at a list containing 38 indicators. The refined shortlist of indicators and corresponding data sources are shown in Table 3.

Data and building blocks for estimation of energy sector composite sustainability index

In the following subsections, we present data coverage, sources, and data preparation. We consider time series data for 27 years from 1991 to 2017 for 38 indicators. We collected data for each of the indicators from various national and international published sources. The data source for each of the indicators is mentioned in Table 3. We faced missing data problem for seven indicators, and the missing values are 8.7% of our total data set. For example, the pump price of gasoline and diesel data are available at two-year intervals. In the case of Bangladesh, price is controlled by the government, and it does not change frequently. Thus, we imputed the missing values of these two variables considering the available time series of gasoline and diesel prices. We used trend analysis to get a good fit represented by R^2 value and imputed the missing values for the missing observations.

Estimating normalized value from the data on indicators

In real-life situation, data corresponding to indicators are measured in different units (access level in percentage of people/households, electricity in kWh, etc.) Thus, it is essential to normalize them to help comparability and aggregation. In the normalization process, the standardized value of each indicator value is estimated using Eq. (1) based on the observed and the sustainability threshold values. Sustainability threshold value for each indicator used to compare the sustainability status is the hypothetical value corresponding to a sustainable energy system (Sharma and Balachandra 2018). We use the best/worst case value in the world as threshold value. The normalized values of social, economic, and environmental indicators are reported in Supplementary Material 2 (SM2).

The range defined by the sustainability threshold values and actual value is transformed to a range of 0 and 1, and so is the observed value to a value between 0 and 1.

$$\begin{aligned}&\text{Standardized indicator value}\\&=(\text{Actual value}-\text{Minimum threshold value})\\&/(\text{Maximum threshold value}-\text{Minimum threshold value})\end{aligned}\tag{1}$$

If a higher value indicates sustainability enabler, we use the normalization Eq. (2)

$$V=\frac{V_{\text{act}}-V_{\text{min}}}{V_{\text{max}}-V_{\text{min}}},\tag{2}$$

where V is the indicator normalized value, V_{act} is the actual indicator value, V_{min} is the world minimum value of the indicator, and V_{max} is the corresponding world maximum value.

And if a smaller value is indicating sustainability, the normalization equation becomes

$$V=\frac{V_{\text{max}}-V_{\text{act}}}{V_{\text{max}}-V_{\text{min}}}.\tag{3}$$

Each indicator value in the data set was normalized using Eqs. (2) and (3). Table 4 lists the upper and lower threshold values taken.

Composite index estimation

For estimating a composite index from the individual index values for each of the 38 indicators, we consider the most widely used formula of the weighted sum method (Nardo et al. 2005) using the Eq. (4)

$$\text{CI}=\sum_{i=1}^{Q}I_iW_i,\tag{4}$$

where W_i and I_i denote the weight and index value of the indicator i, respectively and $\sum_i W_i=1$

Again, the weight that denotes the importance of each indicator in a composite index needs to be calculated. At first, we applied PCA for social, economic, and environmental indicators separately to estimate the weight of individual indicators under respective dimensions. Using these weights, we estimated the social, economic, and environmental sustainability indices. Then, we again applied the PCA of these three calculated indices and calculated each dimensional index's weight for calculating the overall sustainability index for energy sector of Bangladesh.

Table 5 shows weighting and normalization methodologies mentioned by OECD 2008 and used by different energy-related literature from 2015 to 2019 for developing the composite index.

Review of the literature (Table 5) on composite index development methodologies for energy sector assessment clearly shows that the weighted sum method is widely used, with the Min–Max technique used for normalization and the equal weight technique used for weighting. But the recent studies such as Asbahi et al. (2019) justifies the superiority of Principal Component Analysis (PCA)-based weighting technique as it is data driven and can overcome ad hoc and subjective weights of different indicators. Besides, Sharma and Balachandra (2018), compare sustainability with a hypothetical benchmark sustainable system with best indicator values across national systems in the world. Therefore, the specific research gap is the development of composite index for Bangladesh's energy sector sustainability assessment using data-driven method and comparing sustainability with world best and worst hypothetical sustainable energy system. Depending on our goal of estimating sustainability index from a single country perspective, the Min–Max method is used for normalization, and the Principal Component Analysis (PCA) method is used for weighting. The SPSS Commercial Software Package is used to run PCA and to carry out other related statistical procedures. Detailed steps followed are narrated below.

Weighting

Principal Component Analysis (PCA) is used for calculating the weight of each indicator. If we have a complex data set consisting of a huge number of variables and if the variables are highly correlated, PCA becomes an effective way to get an appropriate summary by reducing the number of variables that also simplify the subsequent analysis (Landau and Everitt 2004; Li et al. 2012). To deal with the number of highly correlated indicators and large data set, we choose PCA (a) to reduce the dimension of the data set for simplification so that it can provide meaningful information and make the subsequent analysis easier (b) to get the data-driven weight of the indicators according to their performance that can effectively use for regulatory analysis. We have followed (Nardo et al. 2005; Nicoletti et al. 2000; OECD 2008) guidelines for performing PCA. These include several steps:

Step-1: The first step is to measure the correlations between the basic indicators. A correlation matrix (q × q) is calculated using the following Pearson (1896) correlation coefficient formula.

$$\text{Correlation Matrix},R=\begin{bmatrix}r_{11} & r_{12}\cdots\cdots & r_{1q}\\ r_{21} & r_{11}\ \cdots\cdots & r_{2q}\\ \cdot & \cdot & \cdot\\ \cdot & \cdot & \cdot\\ \cdot & \cdot & \cdot\\ \cdot & \cdot & \cdot\\ r_{11} & r_{2q}\cdots\cdots & r_{qq}\end{bmatrix},\tag{5}$$

Table 3 Refined short list of indicators

SL	Theme	Sub-theme	Indicator code	Indicator name	Used Data source
1	Social welfare	Energy equity (access)	SO 01	Access to clean fuels and technologies for cooking (% of population)	WB open data
2			SO 02	Income inequality, Gini index	WB open data
3			SO 03	Access to electricity, urban (% of urban population)	WB open data
4			SO 04	Access to electricity, rural (% of rural population)	WB open data
5		Energy equity (equitable energy supply)	SO 05	Share of biofuels and waste in total final energy consumption, %	IEA data
6		Equity (affordability)	SO 06	Pump price for diesel fuel	WB open data
7			SO 07	Pump price for diesel fuel	WB open data
8		Adequacy	SO 08	Electric power consumption (KWh per capita)	WB open data
9	Energy intensity	Overall energy intensity	EC 01	Energy intensity level of primary energy	WB open data
10	Energy intensity	Sectoral energy intensity (end-use)	EC 02	Industrial energy intensity	IEA data
11			EC 03	Agricultural energy intensity	IEA data
12			EC 04	Service sector energy intensity	IEA data
13		Losses in use of energy	EC 05	Electric power transmission and distribution losses	WB open data
14	Energy security	Self-sufficiency	EC 06	NG Reserve to Production Ratio	BP data
15			EC 07	Depletion coefficient of natural gas	BP data
16			EC 08	Energy imports, net (% of primary energy use)	WB open data
17		Diversity	EC 09	Diversification of import counterparts (Herfindahl index)	IEA data
18			EC 10	Diversity of primary energy supply (Shannon–Wiener index)	IEA data
19		Share of renewable energy sources	EC 11	Fossil fuel energy consumption (% of total)	WB open data
20			EC 12	Renewable electricity output (% of total electricity output)	IEA data
21		Supply and production security	EC 13	per capita primary production of energies (including Biofuel and Waste)	WB and IEA data
22	Economic feasibility	Use and production patterns	EC 14	Energy use per capita	WB open data
23			EC 15	Share of productive use of energy (Non-residential energy consumption/total final consumption)	WB and IEA data
24			EC 16	Per capita electricity generation capacity	BPBP annual reports
25			EC 17	Capacity utilization, Hrs	BPBP annual reports
26		Economic factor	EC 18	GDP per Capita in PPP	WB open data
27			EC 19	Urban population (% of total population)	WB open data
28		Investment /FDI	EC 20	FDI use in Power, Gas and Petroleum Sector (% of GDP)	WB open data
29		Investment /FDI	EC 21	Foreign direct investments (% of GDP)	WB open data
30			EC 22	Inflation, GDP deflator (annual %)	WB open data
31	Minimizing environmental impact	Atmosphere (GHG emission)	EN 01	Per capita CO2 emissions	WB open data

Table 3 (continued)

SL	Theme	Sub-theme	Indicator code	Indicator name	Used Data source
32			EN 02	Per capita Methane emissions in the energy sector (metric tons of CO2 equivalent)	WB open data
33		Atmosphere (Air quality)	EN 03	PM2.5 air pollution, mean annual exposure	WB open data
34		Environmental transition (low carbon transition)	EN 04	Renewable energy in total primary energy supply	WB open data
35			EN 05	Electricity production from coal (% of total)	WB open data
36			EN 06	Electricity production from natural gas (% of total)	WB open data
37			EN 07	Electricity production from hydro (% of total)	WB open data
38			EN 08	Electricity production from oil (% of total)	WB open data
39			EN 09	Electricity production from renewables (% of total)	WB open data
40			EN 10	Electricity production from nuclear sources (% of total)	WB open data

WB = World Bank open data (WB 2020c), IEA data (IEA 2020), BPDB annual reports (Bangladesh Power Development Board 2019)and BP data (BP 2020)

$$where\ r_{xy} = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}}. \quad (6)$$

Step-2: The second step is to identify the applicability of PCA for this data set. To do this, we use both Kaiser–Meyer–Olkin (KMO) and Bartlett's test. KMO test measures the suitability of data for PCA by measuring sample adequacy. KMO value ranges from 1 to 0, and it should be at least 0.5 for accepting the analysis, and a high value is desirable. On the other hand, Bartlett's test is a test of the hypothesis that the individual variables are uncorrelated, which means the correlation matrix is an identity matrix. A small value (less than 0.05) indicates this hypothesis is not valid, and PCA analysis of these data set might be useful (Fathurrahman 2016).

Step-3: This step involves the extraction of latent factors by computing the eigenvalues and eigenvectors of the correlation matrix using Eq. (7)

$$|R - \lambda I| = 0, \quad (7)$$

where "I" is a (q × q) identity matrix, R is the indicators correlation matrix, and λ is the eigenvalues. Solution of Eq. (5) provides q number of eigenvalues λ1, λ2, λ3…. λq.

The eigen vectors can be obtained by solving Eq. (8), where F is the eigenvectors matrix with (q × q) elements corresponding to λ (λ1, λ2, λ3…. λq) eigenvalues.

$$(R - \lambda I)F = 0. \quad (8)$$

Each component's contribution of variance can be calculated by the Eq. (9).

$$\text{Contribution of variance} = \frac{\lambda_j}{\sum_{j=1}^{q}\lambda_j}. \quad (9)$$

The component that has the largest eigenvalues holds the most variance. In PCA analysis, the extracted components are arranged according to their eigenvalues so that the first principal component explains the maximum possible proportion of variance, and the second explains the maximum of remaining variance and so on. The cumulative variance contribution identifies the Principal Components (PCs). Standard practice is choosing the components with eigenvalues more than one and cumulatively explain more than 60% variance (OECD 2008).

Step-4: Each component relies on a set of coefficients, usually called "loading", the correlation coefficients between the individual indicator and the component. After selecting principal components, the coefficient of each indicator is calculated in this step by dividing the eigenvectors by the square root of its eigenvalues.

Step-5: The rotation of factors is performed in this step by the varimax method to minimize the number of initial indicators that are high loading on the same component. The factorial axis is transformed, so that each indicator is highly loaded on one of the principal components (PC) for making a more straightforward interpretation of the PCs.

Table 4 Upper and lower threshold values of the indicators

Code	Indicator	Unit	Direction with sustainability	Threshold value (Country, year)		
				Upper	Lower	Source
SO 01	Access to clean cooking fuels and technologies	% pop	positive	100 (Singapore, 2000)	0.15 (Sierra Leone, 2000)	WB
SO02	Income inequality, Gini index	no	negative	100 (Perfect inequality)	0 (Perfect equality)	–
SO03	Access to electricity, urban	%	positive	100 (Singapore, 1991)	9.2261 (Chad, 1998)	WB
SO04	Access to electricity, rural	%	positive	100 (Singapore, 1991)	0 (Rwanda, 1993)	WB
SO05	Share of biofuels and waste in total final energy consumption	%	negative	93.9022 (Congo, Dem. Rep. 2002)	0 (Qatar, 1990)	WB
SO06	Pump price for diesel fuel	US$/liter	negative	3.33 (Eritrea, 2014)	0.00008 (Venezuela, 2016)	WB
SO07	Pump price for diesel fuel	US$/liter	negative	3.3 (Eritrea, 2014)	0.01 (Venezuela, 2014)	WB
SO08	Per cap. Electric power consumption	kWh	positive	25,590.69 (Norway, 2005)	13.5133 (Cambodia, 1995)	WB
EC01	Energy intensity level of primary energy	MJ/USD	negative	57.98816 (Liberia, 1995)	0.001634 (Puerto Rico, 1994)	WB
EC02	Industrial energy intensity	MJ/USD	negative	46.09 (Congo, Dem. Rep., 1998)	0.08 (Puerto Rico, 2012)	WB
EC03	Agricultural energy intensity	MJ/USD	negative	11.1 (Canada, 2007)	0.009273 (Congo, Dem. Rep., 1999)	IEA, WB
EC04	Service sector energy intensity	MJ/USD	negative	6.894709 (Congo, Dem. Rep., 2014)	0.818206 (Singapore, 2017)	IEA, WB
EC05	Electric power transmission and distribution losses	%	negative	66.48993 (Haiti, 2011)	1.790871 (Singapore, 2009)	WB
EC06	NG reserve to production ratio	ratio	positive	1733.766 (Qatar, 2001)	1 (reserve and production equal)	BP
EC07	Depletion coefficient of natural gas	%	negative	100 (when fully depleted)	0 (New discovery make up the depletion)	–
EC08	Net energy imports (% of primary energy)	%	negative	100 (Curacao, 1991)	− 1411.43 (Gabon, 1994, net exporter)	WB
EC09	Import diversification (Herfindahl index)	No	negative	10,000 (single fuel import: Worst Case)	1200 (all sources are equally import: best case)	–
EC10	Primary energy supply diversity (Shannon–Wiener index)	No	positive	1.7902 (equally supplied from all sources)	0.2234 (single fuel supply)	–
EC11	Share of fossil fuel energy consumption	%	negative	100 (Brunei Darussalam, 2003)	1.6397 (Congo, Dem. Rep., 2001)	WB
EC 12	Share of renewable electricity output	%	Positive	100 (Albania, 2015)	0 (Qatar, 2015)	WB
EC13	per capita primary production of energies (including biofuel and waste)	toe	positive	106.1679 (Qatar, 2003)	0 (Curacao, 1991)	IEA
EC14	Energy use per capita	Kg oil eq	Positive	22,120.37 (Qatar, 2004)	63.6697 (South Sudan, 2012)	WB
EC15	Share of productive use of energy (Non-residential / TFC)	%	positive	100 (expected value)	0 (unexpected)	–
EC16	Per capita electricity generation capacity	kw	positive	3.679835 (USA, 2017)	0.019052 (Haiti, 1997)	WB, EIA
EC17	Capacity utilization	%	Positive	100 (expected value)	0 (unexpected)	–
EC18	GDP per Capita in PPP	USD	Positive	124,024.6 (Qatar, 2011)	361.0908 (Mozambique, 1992)	WB
EC19	Share of urban population	%	Positive	100 (Singapore, 1991)	5.491 (Rwanda, 1991)	WB
EC20	FDI in Power, Gas and Petroleum Sector	% GDP	Positive	1.46% (maximum value in data set)	0.37% (minimum value in data set)	–

Table 4 (continued)

Code	Indicator	Unit	Direction with sustainability	Threshold value (Country, year)		
				Upper	Lower	Source
EC21	FDI (% of GDP)	%	Positive	86.61 (Netherlands, 2007)	− 58.32 (Luxembourg, 2007)	WB
EC22	Inflation, GDP deflator (annual %)	%	negative	10	0.1	Arbitrary value
EN01	Per Capita CO2 emissions	ton	negative	70.0422 (Qatar, 1997)	0.0107 (Chad, 1991)	WB
EN02	Per capita Methane emissions in energy sector, CO2 eq	MT	negative	25.5591 (Qatar, 2004)	0.0015 (Malta, 2008)	WB
EN03	PM2.5 air pollution, mean annual exposure, micrograms per m3	–	negative	100.7844 (Nepal, 2010)	5.9031 (Brunei Darussalam, 2017)	WB
EN04	Renewable energy in total primary energy supply	%	Positive	96.00 (Congo Dem. Rep., 2017	0 (Bahrain, 2015)	WB
EN05	Electricity production share from coal sources	%	negative	100 (Botswana, 2008)	0 (Turkmenistan, 2015)	WB
EN06	Electricity production share from natural gas sources	%	Positive	100 (Turkmenistan, 2015)	0 (Botswana, 2008)	WB
EN07	Electricity production share from hydroelectric sources	%	Positive	100 (Albania, 2015)	0 (UAE, 2015)	WB
EN08	Electricity production share from oil sources	%	negative	100 (Gibraltar, 2015)	0 (Albania, 2015)	WB

Data source WB (2020c), IEA (2020), EIA (2020), BP (2020)

Table 5 Weighting and normalizing methodologies used in the literature

SL	Normalization Method	Weighting method	References
1	Ranking, Standardization, Min–Max, Distance to a reference, Categorical scales, Indicators above or below the mean, Cyclical indicators, Balance of opinions (EC), Percentage of annual differences over consecutive years	Equal weighting, Principal component analysis (PCA), Factor Analysis, "benefit of the doubt" (BOD) approach, data envelopment analysis, unobserved components models (UCM), budget allocation processes (BAP), analytic hierarchy processes (AHP), conjoint analysis (CA)	OECD (2008)
2	Min–max	PCA	Agovino et al. (2017) and Asbahi et al. (2019)
3	Min–max	AHP	Shaaban et al. (2018)
4	Min–max	Equal weight	Fathurrahman (2016), Iddrisu and Bhattacharyya (2015) and Sharma and Balachandra (2018)
5	min–max, standardization and percentile rankings	Equal weight	World Economic Forum (2015)
6	Min–max	Entropy	Qu and Liu (2016)
8	–	PCA	Praene et al. (2018)
9	–	Both entropy and multivariate statistical analysis (MVA) method for different level of Indicator	Zhan (2018)
10	Min–Max formula	–	Armin Razmjoo et al. (2019)
11	–	Entropy	Alptekin et al. (2018)
12	–	Equal weight	Lior et al. (2018)
13	–	AHP	Liu et al. (2018)
14	–	Equal weight except country context dimension	World Energy Council (2018)

Step-6: The final step is weight calculation from the rotated factor loadings matrix.

Weight of indicator i in the intermediate composite index j

$$W_{ij} = \frac{(\text{factor loading}_{ij})^2}{\text{eigen value}_j}. \quad (10)$$

$$\text{Overall weight}, W_i = W_{ij} \times \left(\text{expl var}_j\right), \quad (11)$$

where expl var_j is the proportion of variance explained by the intermediate composite index j in total variance. The final weight is obtained through the normalization of the overall weight.

Results and discussion

Following the steps mentioned in Sect. 2, the weights of the individual indicators were calculated using PCA. The correlation matrix for each dimension was calculated using Eqs. (5) and (6). Then, KMO and Bartlett's test was performed to identify the applicability of PCA in these data sets. The KMO and Bartlett's test results of social, economic, and environmental indicators are shown in Table 6. It shows that the KMO test result is well above the critical value of 0.5, and the Bartlett's statistical significances are less than 0.05 for each dimension. Thus, the correlation matrixes of social, economic, and environmental indicators were not identity matrices, and the data were enough to apply PCA for each dimensional indicator.

In the next step, the eigenvalues and eigenvectors of the three correlation matrixes of social, economic, and environmental indicators were calculated by PCA. PCA computed the eigenvalue and eigenvectors of the three correlation matrices, yielding 8 components for social indicators, 22 components for economic indicators, and 8 components for social indicators. A component was extracted if its eigenvalue is more than one. Based on their eigenvalues, the first two components were extracted for the social dimension that explains 96.23% variance cumulatively. Similarly, with the set extraction criteria, PCA extracted three components for the economic dimension that explain 88.41% of total variance cumulatively and two components for the social dimension that explain 91.56% of total variance cumulatively. The extracted PCA components, their eigenvalues, and % of variance explained by them before and after rotation are shown in Table 7.

Now, the components loading was calculated to get the contribution of each initial indicator in the extracted components. Then, varimax rotation was performed to minimize the number of high loading indicators on the same factors/components. We grouped the indicators into intermediate factors using Nicoletti et al. (2000) approach. The indicator was grouped to that component where it provides the highest loading factor (Bold marked). In the case of social indicator, we grouped SO 01, SO 03-08 under factor 1 and indicator SO 02 under factor 2. The final weights of the individual indicators were calculated using the Eqs. (10) and (11) as mentioned in Sect. "Weighting". Rotated loading factor, weight of indicator in factor, and normalized final weight are shown in Table 8.

Similarly, in the case of economic indicators, ten indicators: EC 02–06, EC 11–12, EC 15, EC 21–22 were grouped under factor 1, ten indicators: EC 01, EC 07, EC 09, EC 13–14, EC 16–20 were grouped under factor 2, and the remaining two EC 08 and EC 10 were grouped under factor 3 (Table 9). And, in the case of environmental indicators, EN 01–05, EN 07 were grouped under factor 1, and EN 06 and EN 08 were grouped under factor 2 (Table 10). The final weight of individual indicator under both economic and environmental dimensions were calculated using the Eqs. (10) and (11). Rotated loading factor, weight of indicator in factor, and normalized final weight are shown in Table 9 for economic indicators and Table 10 for environmental indicators.

Using these estimated weights and the normalized value of each indicator, the composite index for each dimension for 1991–2017 was calculated using the Eq. (3). To get overall sustainability, the weight of each dimensional sustainability index was calculated by running PCA again. The KMO value of the calculated yearly dimensional composite index data set was obtained 0.504 ($\gtrdot$ 0.5), and Bartlett's statistical significance is 0.000 ($\lessdot$ 0.05). Thus, PCA is applicable for this data set. Now applying PCA, we extracted two components that can explain 97.67% of total variance cumulatively. The dimensional weight was obtained from the rotated loading factor of these two extracted components. The calculated rotated factor loading, the weight of dimensions in factors, and normalized final weights are shown in Table 11.

The overall composite sustainability index for each year is obtained from the dimensional sustainability index and the calculated dimensional weight by applying the Eq. (3).

The calculated overall composite sustainability index, dimensional sustainability index, and contribution of each

Table 6 KMO and Bartlett's test

Indicators dimension	KMO Value	Bartlett's statistical significance
Social	0.837	0.000
Economic	0.596	0.000
Environment	0.595	0.000

Table 7 Extracted components by PCA

Indicators	Components	Extracted components (before rotation)			Extracted components (after rotation)		
		Eigen values	% variance	Cumulative %	Eigenvalues	% variance	Cumulative %
Social Indicators	1	6.713	83.91	83.91	6.203	77.54	77.54
	2	0.985	12.32	96.23	1.495	18.69	96.23
Economic indicators	1	15.597	70.89	70.89	9.347	42.49	42.49
	2	2.163	9.83	80.72	8.114	36.88	79.37
	3	1.692	7.69	88.41	1.990	9.04	88.41
Environmental Indicators	1	5.244	65.550	65.550	4.798	59.981	59.981
	2	2.081	26.010	91.560	2.526	31.579	91.560

indicator in dimensional sustainability is presented in "Composite sustainability index" and "Contribution of component indicators in the composite index".

Composite sustainability index

The composite sustainability index for the energy sector in Bangladesh for 1991–2017 is shown in Fig. 4. Energy sector in Bangladesh is showing a trend towards sustainable development after 2014.

The dimensional composite indices are shown in Fig. 5. It reflects that social sustainability is improving (improved from 0.411 to 0.544); whereas, environmental sustainability is declining (declined from 0.747 to 0.655) during 1991–2017. On the other hand, economic sustainability is slightly improving after 2014.

The overall sustainability index increased from 0.514 to 0.538 during 1991–2017. The social index increased from 0.411 to 0.544, and the economic index from 0.369 to 0.417 during1991–2017. During the same period, the environmental dimensional index decreased from 0.747 in1991 to 0.655 in 2017. Overall, Bangladesh's energy sector is performing moderately compared to sustainability threshold.

The change in contributions of different dimensional sustainability on the overall sustainability index is shown in Fig. 6. It shows that from 1991 to 2017, the contribution of social indicators increased by 6.97%, and economic indicators increased by 0.82%. In contrast, the contribution of environmental indicators decreased by 7.79%. In Table 12, we present a summary of range of values of indices by dimension, theme, and sub-themes along with weights of individual indicators. Environmental sustainability, while deteriorating still is relatively at higher level than the other two dimensional indices. From the sub-theme index value, it is found that this high environmental sustainability (0.747–0.655) is primarily due to the sub-theme atmospheric GHG emission's high index value (0.998–0.994), which implies Bangladesh's low GHGs emission compared to the threshold value. On the other hand, the sub-thematic index for environmental transition (low carbon transition) (0.704–0.565) deteriorated because of rising share of coal and oil sourced power and reducing share of hydropower in the power generation mix, dragging down environmental sustainability. Although economic sustainability increased moderately over the study period, the index value (0.387–0.418) is low in comparison to both the

Table 8 Weight calculation for social dimensional indicators

Indicators	Rotated factor loading		Weight of indicator in factor		Overall weight	Normalized final weight
	F1	F2	F1	F2		
SO 01	**0.9758**	0.1972	**0.1535**	0.03	0.1237	0.1332
SO 08	**0.9758**	0.1717	**0.1535**	0.02	0.1237	0.1331
SO 06	**−0.9753**	0.0089	**0.1534**	0.00	0.1236	0.1330
SO 07	**−0.9485**	−0.1609	**0.1450**	0.02	0.1169	0.1258
SO 04	**0.9427**	0.2459	**0.1433**	0.04	0.1154	0.1243
SO 05	**0.8860**	0.4462	**0.1265**	0.13	0.1020	0.1098
SO 03	**0.8684**	0.4161	**0.1216**	0.12	0.0980	0.1055
SO 02	−0.1409	**−0.984**	0.00	**0.65**	0.1258	0.1354
Expl. Var	6.2029	1.4953				
Tot Var	7.6982					
Expl./tot, %	80.57	19.43				

Table 9 Weight calculation of indicators for economic dimension

Indicators	Rotated factor loading			Weight of indicator in factor			Overall weight	Normalized final weight
	F1	F2	F3	F1	F2	F3		
EC 05	**0.8983**	−0.0120	−0.1624	**0.0863**	0.0000	0.0133	0.0415	0.0575
EC 12	**−0.8801**	−0.3917	0.0141	**0.0829**	0.0189	0.0001	0.0398	0.0552
EC 03	**−0.8740**	−0.2129	0.0788	**0.0817**	0.0056	0.0031	0.0393	0.0544
EC 06	**−0.8643**	−0.4767	0.0208	**0.0799**	0.0280	0.0002	0.0384	0.0532
EC 02	**−0.7884**	−0.4601	0.1171	**0.0665**	0.0261	0.0069	0.0320	0.0443
EC 11	**−0.7836**	−0.6131	0.0302	**0.0657**	0.0463	0.0005	0.0316	0.0437
EC15	**0.7570**	0.6226	−0.1250	**0.0613**	0.0478	0.0078	0.0295	0.0408
EC 22	**−0.7254**	−0.3621	−0.0299	**0.0563**	0.0162	0.0004	0.0271	0.0375
EC 04	**−0.7191**	−0.5670	0.0394	**0.0553**	0.0396	0.0008	0.0266	0.0368
EC 21	**0.6812**	0.5399	0.2391	**0.0496**	0.0359	0.0287	0.0239	0.0330
EC 16	0.3955	**0.8950**	−0.0185	0.0167	**0.0987**	0.0002	0.0412	0.0570
EC 18	0.5468	**0.8251**	0.0732	0.0320	**0.0839**	0.0027	0.0350	0.0485
EC 14	0.6164	**0.7790**	0.0668	0.0406	**0.0748**	0.0022	0.0312	0.0432
EC 01	0.5367	**0.7782**	0.1943	0.0308	**0.0746**	0.0190	0.0311	0.0431
EC 13	0.6099	**0.7699**	0.1573	0.0398	**0.0730**	0.0124	0.0305	0.0422
EC 07	−0.6308	**−0.7620**	−0.1006	0.0426	**0.0716**	0.0051	0.0299	0.0413
EC 19	0.6526	**0.7472**	0.0970	0.0456	**0.0688**	0.0047	0.0287	0.0397
EC 17	0.2323	**−0.7248**	0.1103	0.0058	**0.0647**	0.0061	0.0270	0.0374
EC 09	0.4056	**0.7179**	−0.2289	0.0176	**0.0635**	0.0263	0.0265	0.0367
EC 20	0.5133	**0.6848**	−0.0912	0.0282	**0.0578**	0.0042	0.0241	0.0334
EC 08	0.1375	−0.1324	**0.9517**	0.0020	0.0022	**0.4552**	0.0466	0.0645
EC 10	0.3449	−0.1265	**−0.8922**	0.0127	0.0020	**0.4000**	0.0409	0.0567
Expl. Var	9.3473	8.1144	1.9898					
Tot Var	19.4515							
Expl/tot Var, %	48.05%	41.72%	10.23%					

Table 10 Weight calculation of indicators for environmental dimension

Indicators	Rotated factor loading		Weight of indicator in factor		Overall weight	Normalized final weight
	F1	F2	F1	F2		
EN 07	**0.9293**	0.1342	**0.1800**	0.0071	0.1179	0.1340
EN 04	**0.9292**	0.3026	**0.1799**	0.0363	0.1179	0.1340
EN 01	**0.9100**	0.3836	**0.1726**	0.0582	0.1131	0.1285
EN 05	**0.8867**	−0.0210	**0.1639**	0.0002	0.1073	0.1220
EN 02	**0.8487**	0.4938	**0.1501**	0.0965	0.0983	0.1118
EN 03	**0.7814**	−0.5026	**0.1272**	0.1000	0.0833	0.0947
EN 06	0.0137	**0.9680**	0.0000	**0.3709**	0.1279	0.1454
EN 08	0.3549	**0.9141**	0.0262	**0.3308**	0.1141	0.1297
Expl. Var	4.7985	2.5264				
Tot Var	7.3248					
Expl/tot Var, %	65.51	34.49				

ideal benchmark 1, and the social and environmental dimensional indices. This low index value is primarily due to the low values obtained for the energy security (0.280–0.258) and economic feasibility (0.232–0.309) themes. The low energy security is a result of a low sub-theme index of self-sufficiency (0.303–0.271), diversity (0.338–0.450), and renewability (0.305–0.116), as well as a very low supply and production security index (0.0009–0.0020). Although the social sustainability index has improved significantly (0.411–0.544), it remains significantly lower than the ideal

Table 11 Weight calculation of dimensional index

Indicators	Rotated factor loading		Weight of indicator in factor		Overall weight	Normalized final weight
	F1	F2	F1	F2		
Environment	**−0.9807**	−0.0634	**0.5016**	0.0040	0.3282	0.3321
Social	**0.9722**	0.1397	**0.4929**	0.0193	0.3225	0.3263
Economic	0.1022	**0.9947**	0.0054	**0.9768**	0.3376	0.3416
Expl. Var	1.9173	1.0129				
Tot Var	2.9302					
Expl/tot Var, %	65.43	34.57				

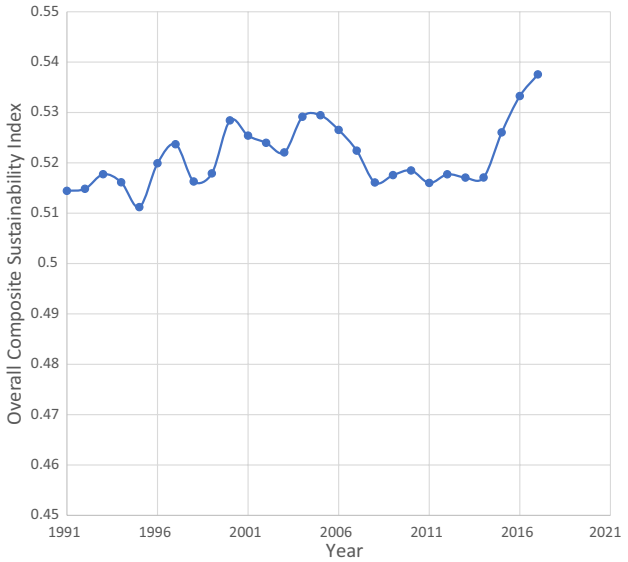

Fig. 4 Overall composite sustainability index for Bangladesh energy sector

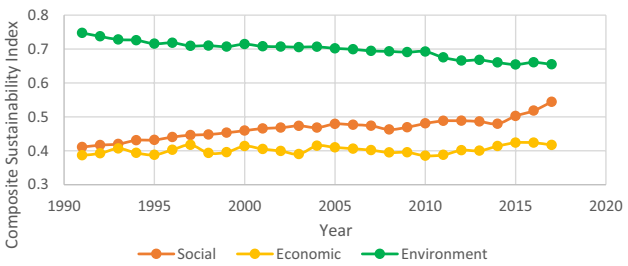

Fig. 5 Dimensional composite index during 1991–2017

benchmark of 1. This lower social sustainability is due to the extremely low index value of adequacy (0.0014–0.0151). Significant progress is being made in the sub-theme of energy equity (access) index (0.331–0.648) because of rural electrification and increasing share of clean cooking fuel and energy equity (equitable energy supply) index (0.417–0.749), which are both contributing to increase social

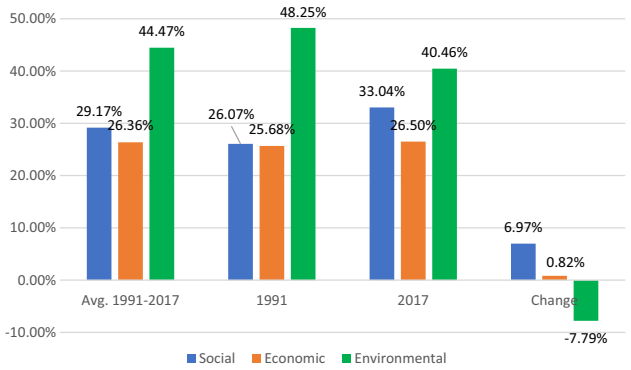

Fig. 6 Change of contribution of dimensional composite index in overall index

sustainability. Although the equity (affordability) index has decreased in value from 0.965 to 0.690, still it remains significantly higher than the other indices.

Contribution of component indicators in the composite index

The contribution of each indicator in the respective dimensional index over the study period was calculated to understand the impact of each indicator on overall sustainability and how these contributions were changing over time.

The contribution of indicators in the social dimensional composite index for 1991 and 2017 are shown in Fig. 7. It shows that the contribution of income inequality, pump price for diesel fuel, and pump price for gasoline fuel decreased from 22.16%, 27.27%, and 25.11% in 1991 to 15.83%, 16.98%, and 13.50% in 2017, respectively. In contrast, the contribution of urban electricity increased from 12.82% in 1991 to 17.90% in 2017, and rural electricity access indicator enhanced from 0.89% in 1991 to 17.24% in 2017. Thus, the improvement of electricity access, especially in rural areas, improved social sustainability during this period. Again, access to clean cooking and per capita electric power

Table 12 Constituent elements of Bangladesh sustainable energy sector dimensional, thematic, and sub-thematic indices

Dimension	Index (1991–2017)	Theme	Index (1991–2017)	Sub-theme	Index (1991–2017)
Social	0.411–0.544	Social welfare	0.411–0.544	Energy equity (access)	0.331–0.648
				Energy equity (equitable energy supply)	0.417–0.749
				Equity (affordability)	0.895–0.690
				Adequacy	0.0014–0.0151
Economic	0.387–0.418	Energy intensity	0.808–0.852	Overall energy intensity	0.936–0.950
				Sectoral energy intensity (end-use)	0.907–0.824
				Losses in use of energy	0.477–0.844
		Energy security	0.280–0.258	Self-sufficiency	0.303–0.271
				Diversity	0.338–0.450
				Renewability	0.305–0.116
				Supply and production security	0.0009–0.0020
		Economic feasibility	0.232–0.309	Use and production patterns	0.211–0.271
				Economic factor	0.075–0.159
				Investment /FDI	0.402–0.503
Environmental	0.747–0.655	Minimizing environmental impact	0.747–0.655	Atmosphere (GHG emission)	0.998–0.994
				Atmosphere (Air quality)	0.418–0.423
				Environmental transition (low carbon transition)	0.704–0.565

consumption had a negligible contribution, and these area needs to be improved to increase social sustainability further.

The contribution of indicators in the economic dimensional composite index in 1991 and 2017 is shown in Fig. 8. It depicts the decreasing contribution of primary energy intensity (from 10.43 to 9.82%), industrial energy intensity (from 10.41 to 9.06%), agricultural energy intensity (from 12.48 to 10.54%), and depletion coefficient (from 10.60 to 9.46%) to economic sustainability between 1991 and 2017. On the contrary, the contribution of electric power transmission and distribution losses increased significantly from 7.09 to 11.63% during this period with the improvement of electricity transmission and distribution system.

Reductions in transmission and distribution losses, as well as increased foreign investment in the energy sector, have aided in raising the economic sustainability index; whereas, increased fossil consumption lowers it. As a whole, energy intensity, renewability, self-energy sufficiency, and investment are the key issues for sustainability with regard to economic dimension in Bangladesh. If transmission and distribution system improve, industrial and agricultural energy efficiency will improve. More investment in renewable energy can help the energy sector to become sustainable in terms of economic dimension. On the other hand, % energy imports, renewable electricity output %, per capita primary production of energies, energy use per capita, GDP per capita have negligible contribution on the composite index through economic dimension.

The contribution of individual indicators in the environmental dimension to composite index for 1991 and 2017 is shown in Fig. 9. CO_2 emissions per capita, share of natural gas, coal, and oil in electricity production are the most contributing indicators in environmental sustainability. It implies that the lower value of these negatively directed indicators, better it is for sustainability. Whereas, % electricity production from hydroelectric sources and air pollution have negligible contributions to it. There are no remarkable changes in the contribution of indicators during 1991–2017,

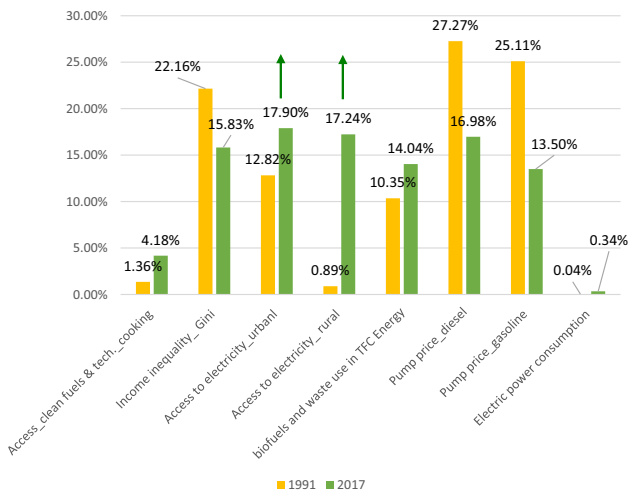

Fig. 7 Contribution of indicators in the social dimensional composite index

except for % of renewable energy in the total primary energy supply (from 10.32 to 5.07%). Thus, we can see that environmental sustainability is becoming worse as Bangladesh is using more and more fossil fuel with the declining share of renewables. To make energy sector environmentally sustainable, it is essential to understand how the penetration of renewables can increase.

In summary, at broader level, this indicator analysis shows that access to electricity, energy efficiency improvement, and renewable energy penetrations need to significantly improve in coming years to make the energy sector sustainable in Bangladesh.

Comparison of energy sector sustainability index for Bangladesh across studies

Comparison of the estimated sustainability index with other studies is possible because they all are presented in pure number index values ranging between 0 and 1. Table 13 shows the comparison of the findings of this study to those of five prior studies that estimated Bangladesh energy sustainability indexes in different years. Along with Bangladesh, study 1 evaluated the energy sustainability of 125 countries in 2014, study 2 calculated the index for 125 countries in 2016, study 3 estimated the index for 30 countries in 2012, study 4 measured the index for 62 countries in 2009, and study 5 accessed the index for 136 countries in 2011.

Table 13 depicts that in the case of the overall sustainability index, the estimates in this study is close to studies 1, 2, and 5. Although, this index value is estimated much lower in studies 2 and 4. In the case of the dimensional indices, this study's environmental sustainability index estimation (0.42) is very close to the estimation of study 1. On the contrary, the estimated economic index (0.52) is lower than the study 1 estimation (0.63); whereas, the social index (0.66) is higher than the study 2 estimation (0.43). These estimation differences can be due to the use of varying indicator set and time periods.

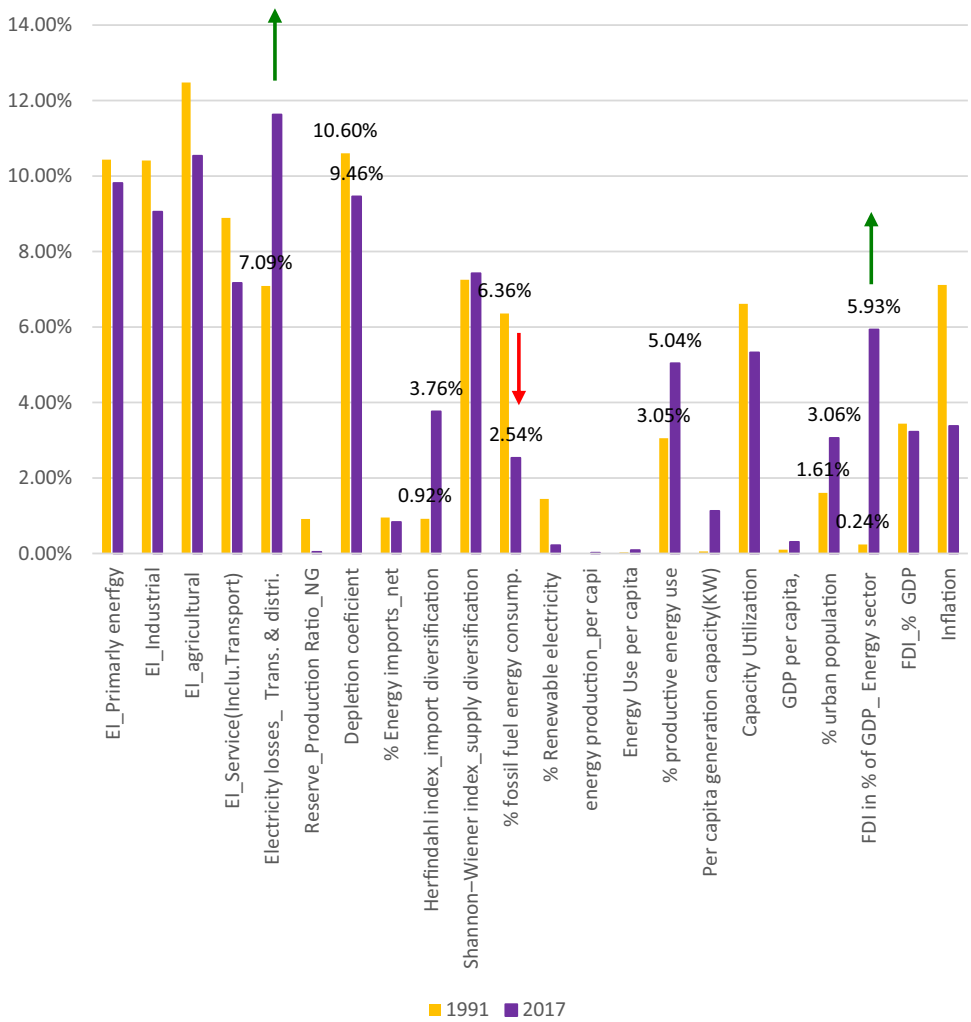

Fig. 8 Contribution of indicators in the economic dimensional composite index

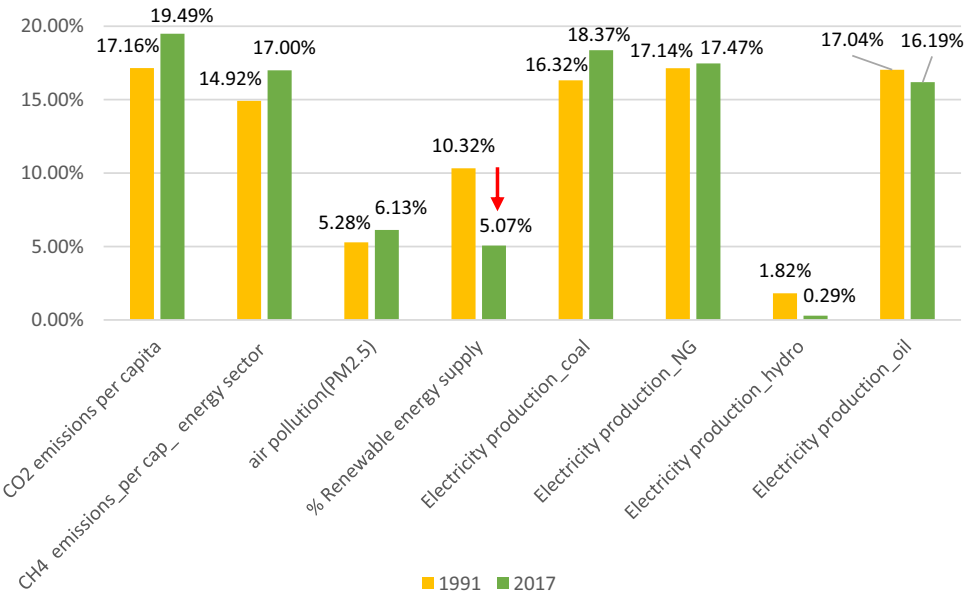

Fig. 9 Contribution of indicators in the environmental dimensional composite index

Conclusions

Our primary goal in this paper was to assess the evidence-based sustainability status of the energy sector in Bangladesh. Indicator-based multi-dimensional hierarchical framework to assess the sustainability status of the energy sector of Bangladesh helped in identifying strong and weak points of the sustainability challenges for the energy sector development. A context-specific list of 38 indicators for Bangladesh has 8 indicators representing social dimensions, economic dimension is represented by 22 indicators, and environmental dimension contains the remaining 8 indicators. A composite sustainability index was estimated to assess the overall sustainability status of the energy sector. To avoid subjectivity, we followed an objective method to calculate the weights of the indicators through Principal Component Analysis (PCA). The overall index value increased from 0.514 to 0.538 during 1991–2017 indicating marginal progress towards sustainability of the energy sector of Bangladesh over the said time period. The highest contribution to this progress is coming from social dimensions and marginally from economic dimensions. Priority given to socio-economic development over this long period of 27 year, just as any other country in the world during their fast-growing phase eventually ignored environmental indicators, resulting in a deteriorating performance in environmental dimension. In the initial years of 1991–2017, index value was ~ 0.75 for environmental dimension. If this could have been maintained, along with positive growth in social and economic indicators, the national energy sector sustainability index could have been much higher than currently recorded 0.54. So, to advance sustainability of the energy sector, environmental themes should get priority along with social and economic themes, and sub-themes. Positives progress of social dimension of energy sector sustainability is driven by increased access to electricity, particularly in rural areas from 3 to 81%; increased access to clean cooking fuel from 5 to 19%; rising per capita electric power consumption 8% annually; and reducing share of solid biofuel and waste

Table 13 Comparison of the results of this study with other five studies

Dimension	Year	This study	Study 1	Study 2	Study 3	Study 4	Study 5
Overall sustainability	2016	0.53	0.50	0.52	–	–	–
	2009	0.52	–		–	0.30	–
	2012	0.52	–		0.26	–	–
	2011	0.52	–		–	–	0.49
Social	2016	0.66	0.45		–	–	–
Economic	2016	0.52	0.63		–	–	–
Environment	2016	0.42	0.43		–	–	–

Study 1 (World Economic Forum 2015), Study 2 (World Energy Council 2016), Study 3 (Fathurrahman 2016), Study 4 (Iddrisu and Bhattacharyya 2015), Study 5 (Agovino et al. 2017)

in energy supply mix 3.2% annually during 1991–2017. In terms of economic indicators, positive impact comes from the improvement of a number of indicators. The transmission and distribution system losses came down from 36 to 12% during 1991–2017. The FDI flow/GDP ratio into the energy sector increased from 0.4 to 1.46% during the same time period. Rising productive use of energy is reflected in increased share of non-residential energy usage in the total energy use (from 28 to 52%). Improvement in diversity of energy supply mix is reflected in Herfindahl index value. Diversity in gas-dependent system was introduced by adding electricity import. While there was no electricity import in 1991, it became 5% of energy import by 2017. But some negative trends are also noteworthy: rising fossil fuel share in the energy supply mix, inflation rate went up from 2.7 to 6.3% during 1991–2017. The energy use per unit of output increased annually 1.78% in industry sector, 1.98% in agriculture sector, and 1.77% in service sector (including transport) during 1991–2017. Most noteworthy is environmental sustainability has deteriorated for Bangladesh over time, primarily due to rising share of oil- and coal-based power and declining relative share of hydropower in the generation mix; declining relative share of renewable energy sources in energy supply mix; per capita methane emission from energy sector increased 2.4% annually during 1991–2017; and per capita CO2 emission rises 4.4% annually during 1991–2017.

The contribution of this research is through evidence-based assessment of sustainability status of the energy sector with policy relevance for Bangladesh. One of the major contributions is in the compilation of the generic sustainable energy sector indicator library with special set of indicators relevant for Bangladesh economy and the time series data for each one of them. Quantitative data-driven sustainability analysis using objective tool like Principal Component Analysis (PCA) is also a contribution in the absence of any such study in the country context. The refined indicator-based tool to assess the sustainability of the national energy systems over time can help in monitoring and tracking progress. This provides clear insights at indicator level where policymaking can help to avoid any negative trend. It compares Bangladesh's energy system to the best indicator value among national energy systems throughout the globe. Such a methodology for comprehensively analyzing sustainability of a national energy system for Bangladesh does not exist, and thus, this study fills that knowledge gap and clearly indicates which aspect needs prioritization. However, for future use and monitoring, we feel that there is an urgent need for creating and maintaining national database on a number of variables which we could not include in the analysis for paucity of data. We recommend that while data on 38 indicators used in this study be maintained, additional efforts be undertaken following systematic annual data collection, reporting, and maintenance for the following list of variables: investment in energy infrastructure, share of installed smart meters, share of clean fuel/renewables in grid electricity, hours and number of electricity supply interruptions, share of household income spent on fuel and electricity, peak shortage, subsidy enjoyed by consumers in various sectors, dependence on import by fuel/energy type, share of various modes of transport in ton km/passenger km with energy use data, energy poverty on percentages, number of skilled technical manpower, and rate of deforestation attributable to energy use.

The research is not devoid of limitations. The index value of the sustainability indicators is strongly dependent on the min–max value of each indicator considered based on world best or worst in the process of normalization. In a dynamic world, these values will evolve over time and the weight of indicator can change with time; so, this study opens up the need for similar comprehensive future studies to track and monitor sustainability performance of the energy sector for Bangladesh and other least developed countries which will experience fast economic growth in this century. Application of PCA method while compressing the dimensionality of a large number of interconnected data sets can lead to loss of some information, but in the current study, loss of information was less than 5–10%. This study provides a good starting point for future studies in the context of Bangladesh in similar direction for helping in selecting policy priorities over time.

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Declarations

Conflict of interest There are no conflicts of interests or competing interests with respect to this manuscript.

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Thematic Section: "Green Transition and National Efforts towards Net-Zero Target"

WHAT TO FOCUS ON IN ORDER TO ACCELERATE ACCESS TO MODERN ENERGY SERVICES AND ENERGY USE EFFICIENCY IN BANGLADESH

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Consistent with national priorities: How can a rapidly growing country, such as Bangladesh, overcome the barriers to realizing Sustainable Development Goal 7? The present study includes an analysis of the barriers to achieving 24x7 access to modern energy and the required improvements to make energy more efficient to overcome them in Bangladesh. Interpretive structural modeling (ISM) is applied to identify the interactions among the barriers as laid out in context-relevant scientific literature. The Cross-impact matrix multiplication applied to classification (MICMAC) is applied to classify the barriers. The results indicate that the barriers can be addressed through a systematic packaging and prioritization approach.

Keywords: Sustainable Development Goal 7; barrier analysis; interpretive structural modeling, rapidly growing economy, developing country

JEL classification: O13, Q49, Q56

I. INTRODUCTION

Bangladesh, one of the most rapidly growing economies in South Asia, recorded annual gross domestic product (GDP) growth of 7.9 per cent in 2019 (World Bank, 2020). To put into context, in Asia, the Republic of Korea and Singapore recorded a GDP annual growth rate that exceeded 8 per cent from1966 to 1990; China recorded annual GDP growth of 9.8 per between 1978 and 2009; Malaysia recorded annual GDP growth of 7.37 per cent from 1961 to 1997. (Mahmud and Roy, 2020). Bangladesh aspires to achieve developed nation status by 2041. Under the national government initiative entitled "Vision 2021" Bangladesh had set a goal of universal access to energy by 2021 (Bangladesh, Ministry of Planning, 2020) and achieved 96.2 per cent access in 2020 (SDG Cell, 2020). More than 88 per cent of the Bangladeshi households have access to electricity; 82 per cent get it from the grid and 6.1 per cent get it from off-grid sources, but 65 per cent of the households experience more than 14 outages per week. For 47 per cent of the households that can use medium- to high-load appliances, electricity is available for at least 8 hours per day and 3 hours per evening. Only 2.6 per cent has 23 hours of electricity service per day with 4 hours of outages per evening and is capable of using very high-power load appliances (Samad and others, 2019).

Over the past forty years, innovations, policies and implementation of energy efficiency initiatives have been proven to be highly effective across various country contexts. Energy efficiency programmes in many countries and sectors have successfully reduced energy use per unit of economic output and led to net improvements in welfare or emission reductions, or in both of them (Saunders and others, 2021). In many countries and many sectors, however, energy efficiency improvements are possible, but gaps persist due to multiple barriers. Among the Asian countries, China, India and Singapore, were able to keep their energy/GDP ratio at less than one during their rapidly growing economic phase whereas the economies of Bangladesh, Malaysia and the Republic of Korea had been expanding while at the same time increasing their energy use per GDP (Roy and others, 2021). Energy efficiency is a critical component of societies' response to the challenges of climate change, economic development and energy security (IEA, 2013). The existing energy efficiency at various industrial activities vis-à-vis the international benchmark and saving potential in Bangladesh show that there is plenty of room for improvement in many industries in this regard, including, among them, those engaged in textiles and steel. (Hartley-Louis and Islam, 2018).

Sustainable Development Goal 7 (affordable and clean energy) is focused on three areas: renewable energy penetration; modern energy access; and energy efficiency improvement by 2030.[1] For this analysis, a comprehensive list of barriers to the accelerated penetration of renewable energy in Bangladesh was developed and the hierarchy among the various individual barriers was analysed (Mahmud and Roy, 2021). Many researchers have attempted to identify specific barriers to 24/7 modern energy access and energy efficiency improvements in Bangladesh, however, no comprehensive literature covering the country exists. However, it is available in other country contexts (Zhao, Chen and Li, 2019), and can be used to illuminate the interconnections and hierarchy among these barriers to help in formulating policy recommendations (Mahmud and Roy and others, 2021). Specific contributions of this present study are to fill this gap in the literature in the context of Bangladesh through the following:

(a) Identification of a list of barriers through a literature review that have been hindering the improvement of 24/7 modern energy access and overall energy efficiency.

(b) Understanding the hierarchical structure of the barriers to obtain a clear understanding of the various layers of the barriers.

(c) Categorizing the barriers as driving barriers, dependent barriers, independent barriers and autonomous barriers to help in guiding actions for overcoming these barriers systematically.

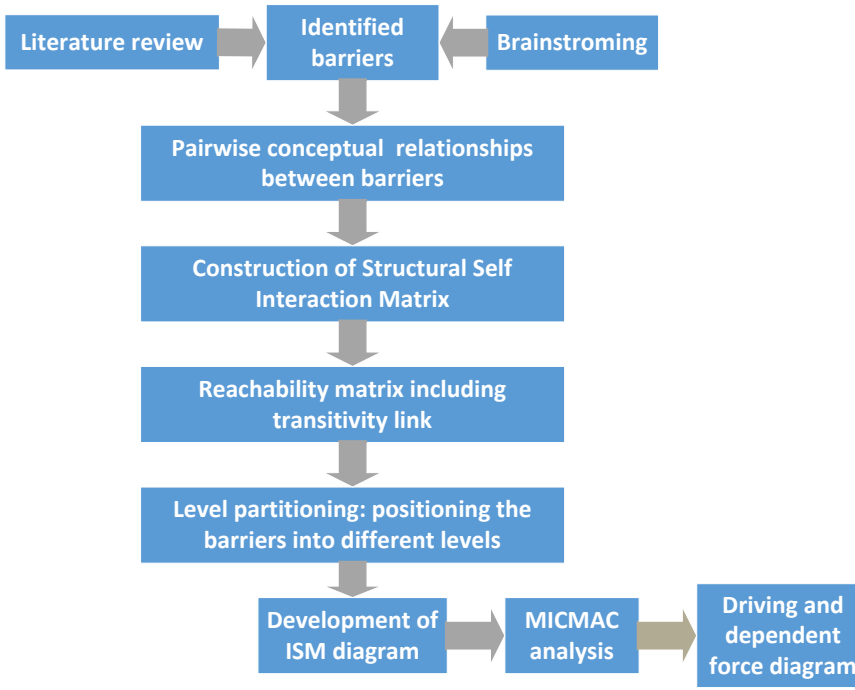
Section 2 gives a description of the methods, materials and research tools used for the analysis the results and discussion are presented in section 3, followed by the conclusions in section 4.

II. METHODS, MATERIALS AND RESEARCH TOOLS

A review of methods in the literature (Mahmud and Roy, 2021) clearly shows the advantage of applying the interpretive structural modeling (ISM) method supplemented by cross-impact matrix multiplication applied to classification (MICMAC) (Yadav and Barve, 2015). How a barrier system works is critical to understand what level of packaging or sequencing needs to adopted overcome them. The steps followed in the ISM process are shown in figure 1.

[1] A/RES/70/1.

Figure 1. Steps followed in interpretive structural modeling



Source: Adapted from Mahmud and Roy (2021)

- Step 1: (a) A comprehensive list of barriers are identified from peer reviewed literature (boxes 1 and 2) and various official reports.
- Step 2: A pairwise conceptual relationship is established between the barriers to develop a structural self-interaction matrix (SSIM).
- Step 3: An initial reachability matrix is formed using SSIM through binary numbers. The final reachability matrix is developed by using the transitivity concept to obtain higher-order links to incorporate the indirect relationships among the barriers using the following relation:
    - Element P related to Q;
    - Q related to R;
    - Implies R is necessarily related to P.

- Step 4: The barriers are positioned into different levels by using the final reachability matrix.
- Step 5: The ISM model is presented using the partitioned level and the relationship given in the reachability matrix.
- Step 6: Cross-impact matrix multiplication applied to classification analysis.
- Step 7: A final figure is developed to show clusters of barriers grouped by their driving power and dependence power.

Data for this study are qualitative in nature. Information about barriers are collected from published peer-reviewed literature on Bangladesh relevant to the objective of this study. From the literature review, an exhaustive list of 14 barriers for "'access to modern energy" ' (listed in box 1) and nine barriers to "energy efficiency improvement" (listed in box 2) are identified. The key applications for which the barriers are assessed are shown in table 1. The allocation of these barriers across eight major dimensions (Mahmud and Roy, 2021) are shown within parenthesis beside each barrier in boxes 1, 2 and 3. It is worth noting that each of the literature reviewed mentions one or the other, or a group of these barriers, but not the comprehensive list as compiled in this study, taking note of overlaps. The authors of this study have decided to identify the links among them without carrying out any further screening, as is sometimes performed by authors (Zhao, Chen and Li, 2019), and then conducted their hierarchy check following the steps mentioned in figure 1 for each of the focus areas.

Table 1. Key energy efficiency and energy access applications in Bangladesh to which the barriers apply

	Energy efficiency for	24/7 Energy access
	Power sector	**Power and energy supply**
1	High efficiency power generation by Combined cycle, tri-generation, multi energy output, among others.	Rural and urban distribution network modernization.
2	Transmission loss reduction, power factor Improvement, theft, leakage, among others.	Reducing peak demand through demand side management
3	Energy management in energy supply plants	Strengthening demand side energy conservation
4		Cross-border power trading

Table 1. *(continued)*

	Industry sector	
5	Efficient industrial process, waste heat recovery, among others	Replacement of captive power by grid power
6	Use of energy efficient technology for industrial motor, boiler, chiller, textile weaving, among others	Improved coordination among electricity generation, transmission and distribution utilities.
7	encourage advanced technology brick kiln and use of non-fired brick	Making the power grid smart, reliable and resilient
	Transport Sector	
8	Penetration of high efficiency vehicle, hybrid car, electric car	Automatic load management and generation scheduling,
9	Mass transportation system in urban area	Appropriate information disclosure mechanisms
10	Improved and enhanced Inland Water Transport (IWT) system	Development of domestic energy resources including offshore exploration in newly acquired sea area
11		Reliable and affordable grid power
	End-use appliances	
10	Use of energy efficient appliances such as split type, inverter type AC with a high coefficient of performance, and variable speed compressor; refrigeration with inverters and variable speed compressor; efficient fans.	Increased use of clean cooking fuels and efficient cooking stoves.
11	Efficient fluorescent lamp, LED bulbs	
	Policy instruments and behaviour change	
12	Appropriate energy pricing, subsidy reduction, time of use based pricing	Proper pricing
13	Change the lifestyle, such as sleeping with the lights off	Consistent policy implementation
14	Awareness raising programme	
15	Energy efficiency labelling programme, such as home appliance rating	

Table 1. *(continued)*

16	Energy Management Program involving, for example, an energy audit, benchmarking,, consumption reporting and large consumer dissemination
	Finance
17	Engage bank personnel on financing EE projects, stimulating investment in energy efficiency activity

Source: Prepared from the literature listed in boxes 1 and 2

Box 1. List of barriers relevant to Bangladesh to accelerate access to modern energy

1. Inefficiency, complexity and unbalanced evaluation of the value chain: (institutional barrier 1)

A bureaucratic culture, complex administrative environment and lack of coordination among generation, transmission and distribution results in policy implementation delays. Value chains involving the electrical and energy sectors, as well as the production, distribution, and transmission sectors, are not adequately explored. Another hurdle is the institutions' insufficient negotiating power for cross-border agreements (Haque, Dhakal and Mostafa, 2020; Hossain, 2020; Islam and others, 2014; Moazzem and Ali, 2019; Sarker, 2017; Economist Intelligence Unit, 2018; Zaman and Brudermann, 2018).

2. Corruption (institutional barrier 2)

Such as illicit gas and electricity connections, meter manipulation, utility employee malfeasance, results in increased system loss and a low connection to bill ratio. These, in turn, increase consumer costs and reduce the energy sector's institutional efficiency (Haque, Dhakal and Mostafa, 2020; Hossain, 2020; Islam and others, 2014; Moazzem and Ali, 2019; Sarker, 2017; Economist Intelligence Unit, 2018; Zaman and Brudermann, 2018).

3. Unfavorable political environment (policy and governance barrier 1)

Over an extended period of time in Bangladesh, the unpredictability of the political environment and the blame culture has led to the frequent

alteration in policy direction and the execution cost of energy and climate-related policies. Political intervention, impact of local politics delays consistent policy formation or results in the implementation of incorrect policies (ADB, 2009; Amin and others, 2019; Haque, Dhakal and Mostafa, 2020; Hossain, 2020; Islam and others, 2014; Moazzem and Ali, 2019; Sarker, 2017; World Bank, 2019; Zaman and Brudermann, 2018).

4. Top-down policymaking (policy and governance barrier 2)

Policies are developed using a top-down approach through a non-transparent centralized bureaucracy in which the participations of stakeholders are missing (ADB, 2009; Amin and others, 2019; Haque, Dhakal and Mostafa, 2020; Hossain, 2020; Islam and others, 2014; Moazzem and Ali, 2019; Sarker, 2017; World Bank, 2019; Zaman and Brudermann, 2018).

5. Inefficient policies (policy and governance barrier 3)

Absence of a suitable energy policy to discourage the use of fossil fuels in power generation in accordance with the nationally distributed commitment (NDC) to climate objectives. Instead, present regulations promote inefficient captive power generation and high-cost quick rental power plants. The tariff policy lacks competitive tariffs, and energy tariffs are influenced by power tariffs. Furthermore, categorizing tariffs for various users does not account for the impact of this pricing on the corresponding user's economic activity (ADB, 2009; Amin and others, 2019; Haque, Dhakal and Mostafa, 2020; Hossain, 2020; Islam and others, 2014; Moazzem and Ali, 2019; Sarker, 2017; World Bank, 2019; Zaman and Brudermann, 2018).

6. Unreliable grid power supply: (technical barrier 1)

Voltage fluctuations, insufficient capacity and failure to modernize the transmission and distribution system, lack of spinning reserves, inefficient dispatch procedures, and outages during peak hours all contribute to the unreliability of grid electricity. This encourages inefficient captive power generation, while also observing idle generation capacity (ADB, 2009; Amin and others, 2019; Hossain, 2020; Islam and others, 2014; Moazzem and Ali, 2019; Zaman and Brudermann, 2018).

7. Exploration and infrastructural limitation for primary energy supply (technical barrier 2)

Inefficient primary energy exploration leads to a deficit in primary energy supply. Offshore exploration activity is very restricted; exploration is delayed

due to sporadic changes in contract choices for gas exploration, despite successful exploration in the same maritime region by neighbouring countries. Coal exploration and production has a relatively limited track record of success. Port capacity is insufficient to fulfil the demand for imports for new power plants (ADB, 2009; Amin and others, 2019; Hossain, 2020; Islam and others, 2014; Moazzem and Ali, 2019; Zaman and Brudermann, 2018).

8. Safety and efficiency (technical barrier 3)

The average efficiency of power plants is lower for low-efficient liquid-based power plants. The sluggish rate of smart prepayment meter installations increases system loss and decreases efficiency. The management safety and disposal of radioactive waste is a major problem associated with nuclear power plants that became operational by 2021 (ADB, 2009; Amin and others, 2019; Hossain, 2020; Islam and others, 2014; Moazzem and Ali, 2019; Zaman and Brudermann, 2018).

9. Inappropriate subsidy allocation and lack of appropriate tariff policy: (economic and financial barrier 1)

The energy subsidy is irrational and trapped in supporting fossil fuel; there is also no long-term tariff strategy for the subsidy. A market-based tariff is missing (ADB, 2009; Amin and others, 2019; Hossain, 2020; Islam and others, 2014; Moazzem and Ali, 2019; World Bank, 2019; Zaman and Brudermann, 2018).

10. Inefficient financing and donor dependent policy (economic and financial barrier 2)

Inadequate financing facility, shortage of long-term capital and dependency on donor agencies hinder progress for reliable excess to modern energy. The policy advice of a donor agency influences the development of energy infrastructure and imbalances the interests of local investors and stakeholders and national policymakers. Additionally, power sector entrepreneurs are more interested in investing in generation rather than transmission and distribution (ADB, 2009; Amin and others, 2019; Hossain, 2020; Islam and others, 2014; Moazzem and Ali, 2019; World Bank, 2019; Zaman and Brudermann, 2018).

11. High cost of grid power and increasing cost of doing business (economic and financial barrier 3)

Expensive liquid fuel, imported liquefied natural gas (LNG), and debt burdens increase the costs for energy-intensive heavy industry (ADB, 2009;

Amin and others, 2019; Hossain, 2020; Islam and others, 2014; Moazzem and Ali, 2019; World Bank, 2019; Zaman and Brudermann, 2018).

12. Depleting local gas reserve and fossil dependency: (resource and environmental barriers)

Depleting local gas reserves creates dependency on imported costlier LNG and reduces the supply of primary energy at affordable prices. Limited supply of local gas promotes expensive liquid-based power generation. Fossil fuel dependency raise emissions over time (Hossain, 2020; Moazzem and Ali, 2019; Economist Intelligence Unit, 2018; World Bank, 2019; Zaman and Brudermann, 2018).

13. Limited disclosure and inaccurate information: (informational barrier)

Informational limitation is a significant barrier. The information disclosure mechanism is very limited. Asymmetric reporting and data variations are common for energy-related information. Absence of accurate demand forecasting in relation to economic activity results in idle generation capacity (Hossain, 2020; Zaman and Brudermann, 2018).

14. Limited cooperation and transactional complexity (geopolitical barrier)

Geopolitical complexity creates significant barriers for an energy-importing county, such as Bangladesh. Insufficient regional cooperation, possible tariff fluctuations and existing contractual limitations has impeded cross-border electricity trade, such as importing clean power from Nepal and Bhutan through India (Haque, Dhakal and Mostafa, 2020; Zaman and Brudermann, 2018).

Box 2. List of barriers relevant to Bangladesh in accelerating energy efficiency improvement

1. Shortage of trained manpower with right skills (human capacity barrier)

Shortage of skilled manpower, technical experts, professionally trained personnel in the industry and financial sectors, for conducting research and development and energy audits and effective energy management, among others (Haque, 2014; Hasan and others, 2019b; Islam and others, 2014).

2. Functional limitation (institutional barriers)

Complexity of collaboration among different energy-related public organizations. Complex bureaucratic system makes the situation worse and cannot influence energy management practices. Association of energy service companies with the relevant industries is very limited (Haque, 2014; Hasan and others, 2019b; Islam and others, 2014).

3. Absence of appropriate regulations (policy and governance barrier)

Lack of adequate regulations covering energy efficiency standards, implementation, financing, pricing, energy management practice and energy audits limits efforts to improve energy efficiency in Bangladesh. Moreover, unfavourable policies impose additional taxes and duties on energy-saving technologies and equipment (Haque, 2014; Hasan and others, 2019a, Hasan, 2019a; Hossain, Sarkar and Pargal, 2017; Islam and others, 2014; Hartley-Lewis and Islam, 2018).

4. Limited research and development and demonstration (technical barrier)

Technological uncertainty, very few research and development activities and limited technological demonstration of energy efficiency (Hasan and others, 2019a; Hasan and others, 2019b; Islam and others, 2014).

5. Limited capital and few private investments (economic and financial barrier 1)

Limited access to finance, high initial cost and difficulties in attracting attract private investment for energy efficiency projects are vital barriers (Haque, 2014; Islam and others, 2014).

6. Unfavourable energy price and future uncertainties (economic and financial barrier 2)

The current low price of energy does not encourage energy savings through energy efficiency measures. In addition, the complexity of non-uniform energy pricing, limited financial incentives and unpredictable future energy prices make it more difficult to implement such measures (Hasan and others, 2019a; Hasan and others, 2019b; Hossain, Sarkar and Pargal, 2017; Islam and others, 2014).

7. Investment preference for production over efficiency: (economic and financial barrier 3)

The preference of investors for production over energy efficiency projects is a barrier to promoting energy efficiency (Hasan and others, 2019a; Hossain, Sarkar and Pargal, 2019; Hasan and others, 2019b; Islam and others, 2014).

8. Lack of technological benchmarks, cost-benefit analysis and other relevant information: (informational barriers 1)

Absence of data collection and poor quality of the information about cost-benefits analysis, technological benchmarks, energy expenditure, opportunities regarding energy efficiency are significant barriers that are limiting efforts to improve energy efficiency (Hasan and others, 2019a; Hasan and others, 2019b; Islam and others, 2014).

9. Lack of awareness (informational barrier 2)

End users, financiers and industrialists are not sufficiently aware of the benefits of energy efficient technologies (Haque, 2014; Hasan and others, 2019a; Hasan and others, 2019b; Hossain, Sarker and Pargal, 2017; Islam and others, 2014).

III. RESULTS AND DISCUSSION

3.1 Barriers to modern energy access: interpretive structural modeling analysis

The findings of a step-by-step ISM analysis are presented in sections 3.1.1 to 3.1.5.

3.1.1 SSIM: structural self-interaction matrix.

The structural self-interaction matrix for modern energy access barriers is presented in table 2. ISIM is built using four types of barrier to barrier pairwise relations (1 through 14) using symbols V,A,X and O.

Table 2. Structural self-interaction matrix for modern energy access barriers

Barriers	14	13	12	11	10	9	8	7	6	5	4	3	2
1	V	O	O	V	O	O	O	V	V	O	O	O	A
2	O	O	O	V	O	O	O	O	V	O	O	A	
3	V	O	V	V	O	V	O	O	O	V	O		
4	O	O	O	O	O	V	O	V	V	V			

Table 2. *(continued)*

Barriers	14	13	12	11	10	9	8	7	6	5	4	3	2
5	O	A	O	V	V	V	V	V	V				
6	A	A	A	V	A	A	O	A					
7	O	A	V	V	A	A	O						
8	O	O	O	O	O	O							
9	O	A	V	V	V								
10	O	A	O	V									
11	A	O	A										
12	A	O											
13	V												

For example, in the SSIM table 2, cell (1,14) is denoted by V because barrier 1 aids in the elimination of barrier 14; cell (1,2) is denoted by A because barrier 1 aids in the abatement of barrier 2; and cell (2,14) is denoted by O because barrier 2 and 14 are unrelated. As there is no barrier pair that helps to alleviate each other, the cell is indicated by X.

3.1.2 Reachability matrix.

Following the rules in table 3, the SSIM in table 2 is converted into the initial reachability matrix by replacing symbols V, A, X, and O with 0 and 1. Table 4 shows the resulting initial reachability matrix.

Table 3. Rules to follow in deriving reachability matrix from the structural self-interaction matrix

Sl. No.	Symbol of (i, j) Cell in SSIM	Substituted in initial reachability matrix	
		Cell (i, j)	Cell (j, i)
1	V	1	0
2	A	0	1
3	X	1	1
4	O	0	0

Source: Table compiled for the purpose of this study using information available from published literature (Ansari and others, 2013).

Table 4. Initial reachability matrix for modern energy access barriers

Barriers	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	0	0	0	0	1	1	0	0	0	1	0	0	1
2	1	1	0	0	0	1	0	0	0	0	1	0	0	0
3	0	1	1	0	1	0	0	0	1	0	1	1	0	1
4	0	0	0	1	1	1	1	0	1	0	0	0	0	0
5	0	0	0	0	1	1	1	1	1	1	1	0	0	0
6	0	0	0	0	0	1	0	0	0	0	1	0	0	0
7	0	0	0	0	0	1	1	0	0	0	1	1	0	0
8	0	0	0	0	0	0	0	1	0	0	0	0	0	0
9	0	0	0	0	0	1	1	0	1	1	1	1	0	0
10	0	0	0	0	0	1	1	0	0	1	1	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0
12	0	0	0	0	0	1	0	0	0	0	1	1	0	0
13	0	0	0	0	1	1	1	0	1	1	0	0	1	1
14	0	0	0	0	0	1	0	0	0	0	1	1	0	1

While the initial reachability matrix is based on direct links, the final reachability matrix incorporates indirect linkages through the use of the transitivity criteria, as indicated in step 3 of the ISM method discussed in section 2. The results show 17 indirect links after conducting first-order transitivity checks, and one additional indirect link after carrying out second- and third-order transitivity checks. For example, if barrier 2 is resolved/reduced, it aids in the mitigation of barrier 1, and barrier 1 aids in the reduction of barrier 14. As a result, overcoming barrier 2 significantly contributes towards the reduction of barrier 14. The resulting final reachability matrix is shown in table 5. In the final reachability matrix, the driving power is determined by counting and adding 1 in each of the barrier's rows, and the dependence is computed by counting and adding 1 in each of the barrier's column.

Table 5. Final reachability matrix for modern energy access barriers

Barriers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Driving Power
1	1	0	0	0	0	1	1	0	0	0	1	1	0	1	6
2	1	1	0	0	0	1	1	0	0	0	1	1	0	1	7
3	1	1	1	0	1	1	1	1	1	1	1	1	0	1	12

Table 5. *(continued)*

Barriers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Driving Power
4	0	0	0	1	1	1	1	1	1	1	1	1	0	0	9
5	0	0	0	0	1	1	1	1	1	1	1	1	0	0	8
6	0	0	0	0	0	1	0	0	0	0	1	0	0	0	2
7	0	0	0	0	0	1	1	0	0	0	1	1	0	0	4
8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
9	0	0	0	0	0	1	1	0	1	1	1	1	0	0	6
10	0	0	0	0	0	1	1	0	0	1	1	1	0	0	5
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
12	0	0	0	0	0	1	0	0	0	0	1	1	0	0	3
13	0	0	0	0	1	1	1	1	1	1	1	1	1	1	10
14	0	0	0	0	0	1	0	0	0	0	1	1	0	1	4
Dependence power	3	2	1	1	4	12	9	5	5	6	13	11	1	5	

3.1.3 Level partitioning.

From the reachability matrix, the reachability set and antecedent set for each of the barriers under consideration can be determined, followed by the intersection of the reachability set and antecedent set for each barrier. Barriers 8 and 11 are positioned in level I in the case of modern energy access barriers because they have the same element in the reachability set and intersection set (table 6). In the second iteration (table 7), these two barriers are omitted. This method is continued until all of the barrier levels are determined; the findings are presented in tables 8 to 12.

Table 6. Level partitioning of modern energy access barriers: stage 1

Elements	Reachability	Antecedent	Intersection	Level
1	1,6,7,11,12,14	1,2,3	1	
2	1,2,6,7,11,12,14	2,3	2	
3	1,2,3,5,6,7,8,9,10,11,12,14	3	3	
4	4,5,6,7,8,9,10,11,12	4	4	
5	5,6,7,8,9,10,11,12	3,4,5,13	5	
6	6,11	1,2,3,4,5,6,7,9,10,12,13,14	6	

Table 6. *(continued)*

Elements	Reachability	Antecedent	Intersection	Level
7	6,7,11,12	1,2,3,4,5,7,9,10,13	7	
8	8	3,4,5,8,13	8	I
9	6,7,9,10,11,12	3,4,5,9,13	9	
10	6,7,10,11,12	3,4,5,9,10,13	10	
11	11	1,2,3,4,5,6,7,9,10,11,12,13,14	11	I
12	6,11,12	1,2,3,4,5,7,9,10,12,13,14	12	
13	5,6,7,8,9,10,11,12,13,14	13	13	
14	6,11,12,14	1,2,3,13,14	14	

Table 7. Level partitioning of energy access barriers: stage 2

Elements	Reachability	Antecedent	Intersection	Level
1	1,6,7,12,14	1,2,3	1	
2	1,2,6,7,12,14	2,3	2	
3	1,2,3,5,6,7,9,10,12,14	3	3	
4	4,5,6,7,9,10,12	4	4	
5	5,6,7,9,10,12	3,4,5,13	5	
6	6	1,2,3,4,5,6,7,9,10,12,13,14	6	II
7	6,7,12	1,2,3,4,5,7,9,10,13	7	
9	6,7,9,10,12	3,4,5,9,13	9	
10	6,7,10,12	3,4,5,9,10,13	10	
12	6,12	1,2,3,4,5,7,9,10,12,13,14	12	
13	5,6,7,9,10,12,13,14	13	13	
14	6,12,14	1,2,3,13,14	14	

Table 8. Level partitioning of modern energy access barriers: stage 3

Elements	Reachability	Antecedent	Intersection	Level
1	1,7,12,14	1,2,3	1	
2	1,2,7,12,14	2,3	2	
3	1,2,3,5,7,9,10,12,14	3	3	
4	4,5,7,9,10,12	4	4	
5	5,7,9,10,12	3,4,5,13	5	
7	7,12	1,2,3,4,5,7,9,10,13	7	
9	7,9,10,12	3,4,5,9,13	9	
10	7,10,12	3,4,5,9,10,13	10	
12	12	1,2,3,4,5,7,9,10,12,13,14	12	III
13	5,7,9,10,12,13,14	13	13	
14	12,14	1,2,3,13,14	14	

Table 9. Level partitioning of modern energy access barriers: stage 4

Elements	Reachability	Antecedent	Intersection	Level
1	1,7,14	1,2,3	1	
2	1,2,7,14	2,3	2	
3	1,2,3,5,7,9,10,14	3	3	
4	4,5,7,9,10	4	4	
5	5,7,9,10	3,4,5,13	5	
7	7	1,2,3,4,5,7,9,10,13	7	IV
9	7,9,10	3,4,5,9,13	9	
10	7,10	3,4,5,9,10,13	10	
13	5,7,9,10,13,14	13	13	
14	14	1,2,3,13,14	14	IV

Table 10. Level partitioning of modern energy access barriers: stage 5

Elements	Reachability	Antecedent	Intersection	Level
1	1	1,2,3	1	V
2	1,2	2,3	2	
3	1,2,3,5,9,10	3	3	
4	4,5,9,10	4	4	
5	5,9,10	3,4,5,13	5	
9	9,10	3,4,5,9,13	9	
10	10	3,4,5,9,10,13	10	V
13	5,9,10,13	13	13	

Table 11. Level partitioning of modern energy access barriers: stage 6

Elements	Reachability	Antecedent	Intersection	Level
2	2	2,3	2	VI
3	2,3,5,9	3	3	
4	4,5,9	4	4	
5	5,9	3,4,5,13	5	
9	9	3,4,5,9,13	9	VI
13	5,9,13	13	13	

Table 12. Level partitioning of modern energy access barriers: stage 7

Elements	Reachability	Antecedent	Intersection	Level
3	3,5	3	3	VIII
4	4,5	4	4	VIII
5	5	3,4,5,13	5	VII
13	5,13	13	13	VIII

The level partitioning technique entails creating eight levels of hierarchy for the 14 barriers. The top ones in hierarchy are barriers 8 and 11 while barriers 3, 4, and

13 are at the bottom. As a bottom-level barrier has the greatest influence on all other barriers in the hierarchy above it, the barriers at level VIII in the analysis (barrier #3 – unfavourable political environment; barrier #4 – top-down policymaking, barrier #13 – limited disclosure and inaccurate information) require the most attention and highest priority in order to overcome all other barriers and accelerate modern energy access in Bangladesh. On the other hand, the top-level barriers (barrier #8 – safety and efficiency; and barrier #11 – high cost of grid power and increasing cost of doing business) do not affect the other barriers positioned in the lower-levels.

3.1.4 Barrier hierarchy.

Hierarchy of the ISM hierarchy model is built by utilizing the level partitioning and final reachability matrix (figure 2), top-level barriers, #8 –safety and efficiency, and #11 – high cost of grid power and increasing cost of doing business, and the bottom level (level VIII) barriers. #3 – unfavourable political environment, #4 – top-down policymaking, and #13 – limited disclosure and inaccurate information. Between the top and bottom levels, there are institutional, geopolitical, informational, resource, and environmental barriers in the ISM hierarchy.

3.1.5 The cross-impact matrix multiplication analysis.

MICMAC analysis is used to classify the barriers into four groups, namely autonomous, independent, linkage and dependent. There is no linkage barrier. The dependent barriers are #6 (unreliable grid power supply: technical barrier 1), #7 (exploration and infrastructural limitation for primary energy supply: technical barrier 2), #11 (high cost of grid power and increasing cost of doing business: economic and finance barrier 3), and #12 (depleting local gas reserve and future greenhouse emission rise: resource and environment barrier), which appear in the upper section of the ISM hierarchy. They are affected by the four independent barriers: #3 (unfavourable political environment: policy and governance barrier 1), #4 (top-down policymaking: policy and governance barrier 2), #5 (Inefficient policy: policy and governance barrier 2), and #13 (limited disclosure and inaccurate information: informational barrier 1). These independent barriers are the most important and are at the bottom of the ISM hierarchy. Barriers #1 (inefficiency, complexity and unbalance evaluation of value chain: institutional barrier 1), #2 (corruption: institutional barrier 2), #8 (safety and efficiency: technical barrier 3), #9 (inappropriate subsidy allocation and lack of appropriate tariff policy: economic and finance barrier 1), #10 (inefficient financing and donor dependent policy: economic and finance barrier 2), #14 (limited cooperation and transactional complexity: geopolitical barrier), are autonomous barriers that have limited interaction with other barriers and are in the middle of the ISM hierarchy. The results from the cross-impact matrix multiplication applied to classification analysis, the distribution of barriers by various typology, for energy access barriers are shown in figure 3.

Figure 2. Interpretive structure modelling framework for modern energy access barriers

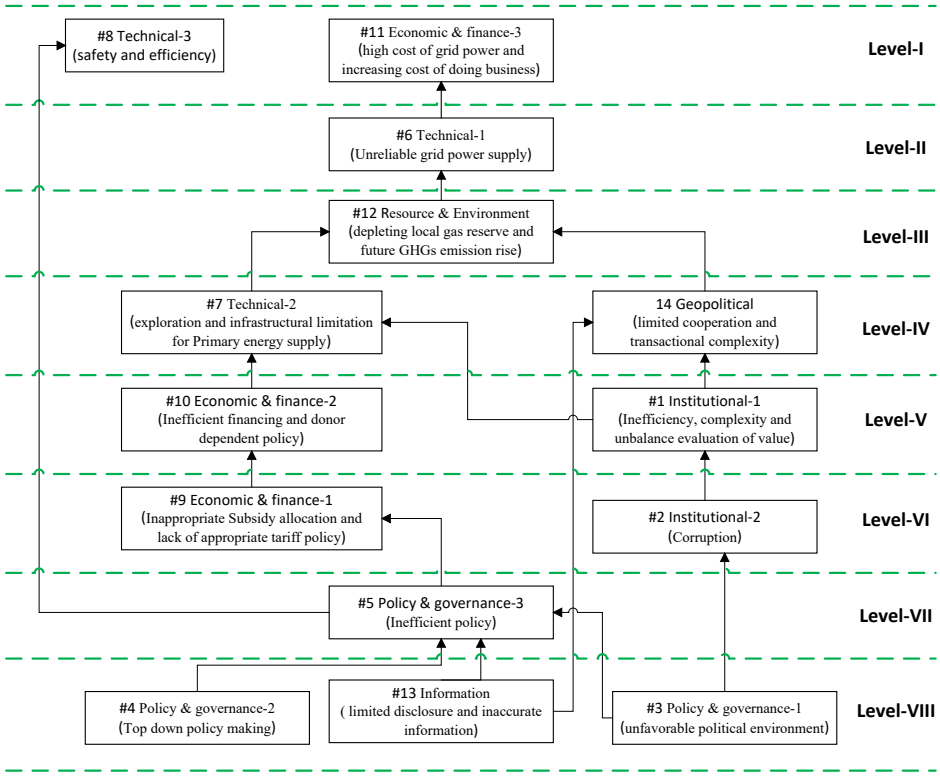
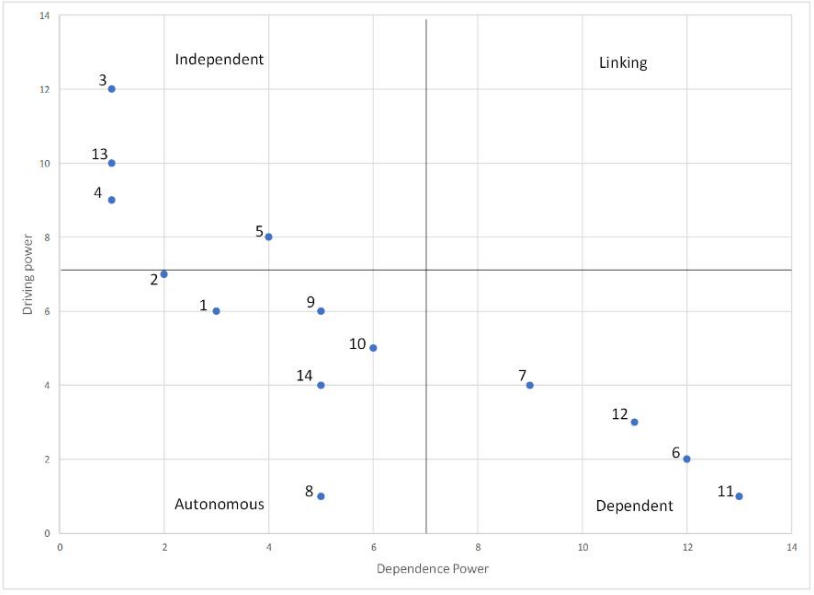


Figure 3. Barriers with varying driving and dependence power from cross-impact matrix multiplication applied to classification analysis



3.2 Interpretive structural modeling analysis for energy efficiency improvement barriers

The analysis and the findings for energy efficiency barriers are illustrated in sections 3.2.1 to

3.2.1 Structural self-interaction matrix.

SSIM for energy efficiency barrier are shown in table 13, in which four symbols V, A, O and X ,are used to represent the pairwise conceptual relationship between the barriers.

Table 13. Structural self-interaction matrix for renewable energy penetration barriers

Barriers	9	8	7	6	5	4	3	2
1	O	V	O	O	O	V	V	V
2	O	A	O	O	V	O	A	
3	O	A	V	V	V	O		

Table 13. *(continued)*

Barriers	9	8	7	6	5	4	3	2
4	O	O	V	O	V			
5	A	A	A	A				
6	O	O	V					
7	A	A						
8	V							

3.2.2 Reachability matrix.

Y replacing the symbols V, A, X and O with 0 and 1, SSIM in table 13 is converted into an initial reachability matrix shown, as shown in table 14.

The indirect linkages are incorporated in the final reachability matrix through transitivity tests using the transitivity criterion, as described in step 3 of the ISM approach in section 2. After completing first- and second-order transitivity tests, five indirect connections among energy efficiency barriers are discovered, which are incorporated into the final reachability matrix, shown in table 15. As an example of an indirect link, barrier 8 affects barrier 3, and barrier 3 influences barrier 6, therefore, barrier 8 indirectly influences barrier 6. As a result, cell (8, 6) which is represented by 0 in the initial reachability matrix (table 14) is substituted by 1 in the final reachability matrix (table 15). From the final reachability matrix, the driving power of a barrier is determined by counting and adding 1 in the corresponding rows, whereas dependency is measured by tallying and adding 1 in the column of the barrier (table 15).

Table 14. Initial reachability matrix for energy efficiency improvement barriers

Barriers	1	2	3	4	5	6	7	8	9
1	1	1	1	1	0	0	0	1	0
2	0	1	0	0	1	0	0	0	0
3	0	1	1	0	1	1	1	0	0
4	0	0	0	1	1	0	1	0	0
5	0	0	0	0	1	0	0	0	0
6	0	0	0	0	1	1	1	0	0
7	0	0	0	0	1	0	1	0	0
8	0	1	1	0	1	0	1	1	1
9	0	0	0	0	1	0	1	0	1

Table 15. Final reachability matrix for energy efficiency improvement barriers

Barriers	1	2	3	4	5	6	7	8	9	Driving power
1	1	1	1	1	1	1	1	1	1	9
2	0	1	0	0	1	0	0	0	0	2
3	0	1	1	0	1	1	1	0	0	5
4	0	0	0	1	1	0	1	0	0	3
5	0	0	0	0	1	0	0	0	0	1
6	0	0	0	0	1	1	1	0	0	3
7	0	0	0	0	1	0	1	0	0	2
8	0	1	1	0	1	1	1	1	1	7
9	0	0	0	0	1	0	1	0	1	3
Dependence power	1	4	3	2	9	4	7	2	3	

3.2.3 Level partitioning gives the relative importance of the barriers. In this analysis, barrier 5 is assessed as level I barriers from the first stage iteration (table 16) and is omitted in the subsequent iterations. In this approach six hierarchy levels of barriers are identified; the findings are presented in tables 17 to 19.

Table 16. Level partitioning of energy efficiency improvement barriers: stage 1

Elements	Reachability	Antecedent	Intersection	Level
1	1,2,3,4,5,6,7,8,9	1	1	
2	2,5	1,2,3,8	2	
3	2,3,5,6,7	1,3,8	3	
4	4,5,7	1,4	4	
5	5	1,2,3,4,5,6,7,8,9	5	I
6	5,6,7	1,3,6,8	6	
7	5,7	1,3,4,6,7,8,9	7	
8	2,3,5,6,7,8,9	1,8	8	
9	5,7,9	1,8,9	9	

Table 17. Level partitioning of energy efficiency improvement barriers: stage 2

Elements	Reachability	Antecedent	Intersection	Level
1	1,2,3,4,6,7,8,9	1	1	
2	2	1,2,3,8	2	II
3	2,3,6,7	1,3,8	3	
4	4,7	1,4	4	
6	6,7	1,3,6,8	6	
7	7	1,3,4,6,7,8,9	7	II
8	2,3,6,7,8,9	1,8	8	
9	7,9	1,8,9	9	

Table 18. Level partitioning of energy efficiency improvement barriers: stage 3

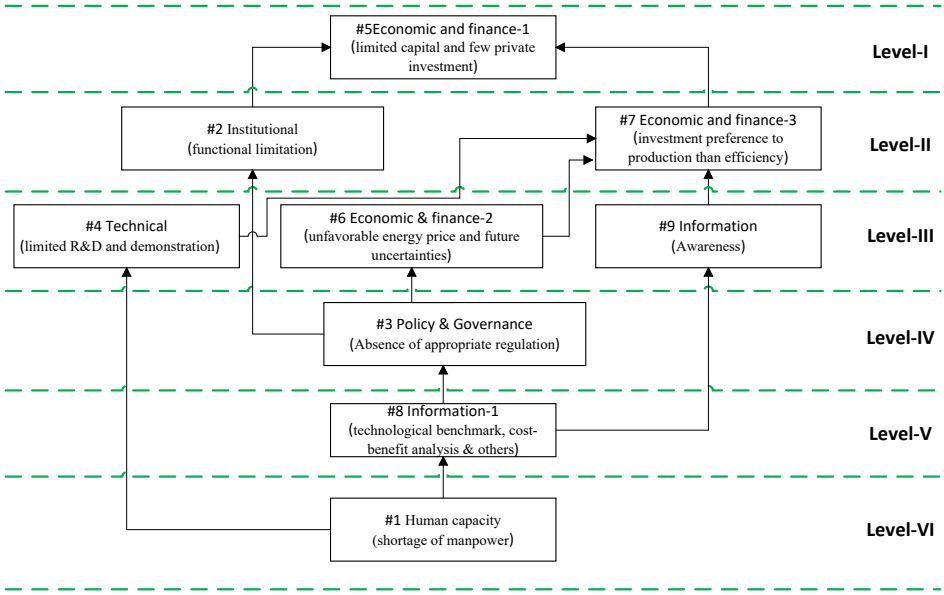
Elements	Reachability	Antecedent	Intersection	Level
1	1,3,4,6,8,9	1	1	
3	3,6	1,3,8	3	
4	4	1,4	4	III
6	6	1,3,6,8	6	III
8	3,6,8,9	1,8	8	
9	9	1,8,9	9	III

Table 19. Level partitioning of Energy Efficiency Improvement Barriers: stage 4

Elements	Reachability	Antecedent	Intersection	Level
1	1,3,8	1	1	VI
3	3	1,3,8	3	IV
8	3,8	1,8	8	V

3.2.4 Barrier hierarchy: The barriers are positioned in the hierarchy diagram according to their hierarchy level estimated in section 3.2.3. The arrows show the direction of interaction between two barriers. Figure 4 depicts the established ISM model for energy efficiency improvement barriers in Bangladesh; #5 (limited capital and few private investments; economic and financial barrier 1) is at the top level (level 1) and #1 (shortage of manpower: human capacity barrier) is at the bottom level (level VI). Between the top and lowest levels, are the technical, policy and governance, informational, institutional, and resource and environment barriers.

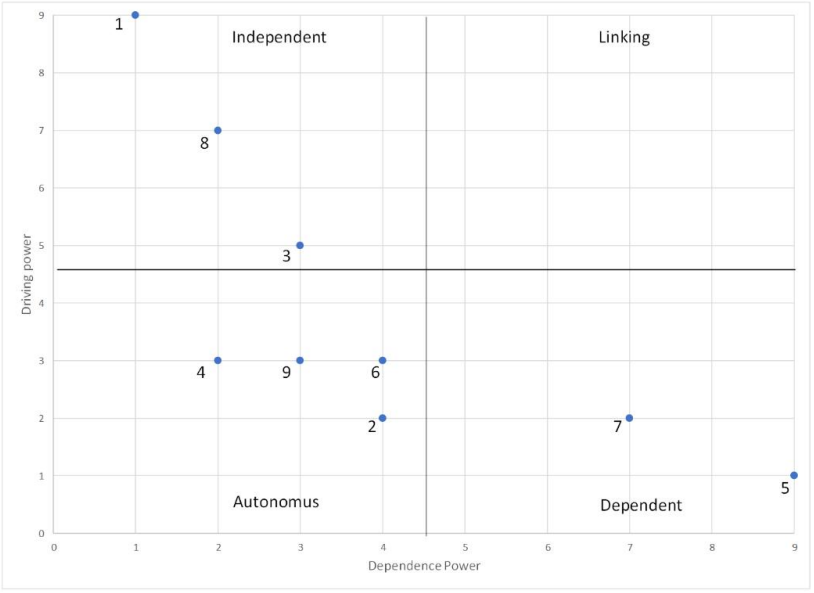
Figure 4. Interpretive structural modelling model framework for energy efficiency barriers



3.2.5 Cross-impact matrix multiplication applied to classification analysis: three independent, four autonomous and two dependent barriers are identified. Barriers #1 (shortage of manpower: human capacity barrier), #3 (absence of appropriate regulation: policy and governance barrier), and #8 (limited technological benchmark, cost-benefit analysis, and others: information 1) are independent barriers set in the lower portion of the ISM hierarchy. These are the most important barriers and have a significant impact on the dependent barriers: #5 (limited capital and few private investments: economic and finance barrier 1) and #7 (investment preference for production over efficiency: economic and finance barrier 3), which are at the upper part of the ISM hierarchy. Barriers #2 (functional limitation: institutional barrier),

#4 (limited research and development and demonstration: technical barrier 2), #6 (unfavourable energy price and future uncertainties: economic and finance barrier 2), and #9 (lack of awareness: information barrier 2), on the other hand, are autonomous barriers that have limited interaction with other barriers and are at the between the top and bottom levels of the ISM hierarchy. Figure 5 depicts the MICMAC results with their corresponding classifications.

Figure 5. Barriers with varying driving and dependence power indicated by the cross-impact matrix multiplication applied to classification analysis



Based on the ISM study on modern energy access barriers (figure 2), the most significant barriers for enhancing modern energy access are top-down policy formulation (#4), adverse political conditions (#3), and limited disclosure and inaccurate information (#13). As a result, the policy may become inefficient and ineffective (# 5). In the MICMAC study, they were identified as driving barriers (figure 3), which shows how the combined influence of these four barriers influence the other barriers, such as inappropriate tariff policy and subsidy allocation (#9), institutional inefficiency (#1), limited financing (#10), and exploration and infrastructure limitations in primary energy supply (#7). The end result is inconsistent grid power supply (#6) and high grid power costs (#11), which limit access to modern energy in Bangladesh.

Based on an ISM analysis, the major impediment to improving energy efficiency in Bangladesh is lack of skilled labour (figure 4). Aside from human capacity limitations (#1), based on the MICMAC analysis (figure 5), two other driving barriers were lack of suitable regulations (#3) and technical benchmark, cost-benefit analysis, and other relevant information limitations (#8). The collective impact of these three driving barriers exacerbates additional barriers, such as insufficient research and development (#4), institutional functional complexity (#2), unfavourable pricing (#6) and limited awareness (#9). The final barrier is lack of financial capital and low private investments (#5) and a bias towards investment in energy supply enhancement reflecting the preference for investing in gross output increase rather than in efficiency enhancement in the production process (#7), which limits efforts to improve overall energy efficiency in Bangladesh.

IV. CONCLUSION

This study makes an important contribution by presenting a comprehensive list of factors that act as barriers to accelerating improvements in energy efficiency and access to modern energy in Bangladesh. An analysis is conducted using an ISM framework and the cross-impact matrix multiplication applied to classification approach to find out how the barriers can be overcome by addressing them independently and/or in clusters/packages. While human capacity-building can be prioritized independently to enhance energy efficiency, to address energy access, lack of information, political interference, top down policy practices need to be considered together to overcome the barriers]. For this study, published literature is used to identify fourteen distinct barriers to modern energy access, and nine distinct barriers for improvement in energy efficiency in the context of Bangladesh. However, the systematic analysis helps in concluding that all fourteen barriers to modern energy access, and nine barriers for improvement in energy efficiency can be considered as interlinked systems in which no single barrier can be ignored. To remove barriers, a big push needs to come from strategic actions through regulations, more implementation of comprehensive energy policies that reflects the government's commitment to address multiple barriers and an incentive design for private sector investment. A whole policy portfolio with a strategic mix and sequencing of interlinked policies are necessary without losing sight of any one of the barriers.

Policy to advance progress in energy efficiency in Bangladesh cannot ignore factors, such as , the shortage of manpower and the need for research and development and energy auditing and energy management,. If long-term policies were to be put in place to regulate energy efficiency standards in various sectors, financing and energy management practices and energy audits would follow, but institutional arrangements could emerge through policy and regulations, as has been experienced in many other

countries. Unfavourable conditions, such as additional taxes and duties on energy-saving technologies and equipment and limited information about cost-benefits analysis for energy efficiency improvement programmes and projects, and the development of a technological benchmark for energy efficiency improvement must be addressed immediately. Actions to address these factors would contribute towards tackling other barriers, such as the preference of investors for energy production projects over energy efficiency projects, limited capital and few private investments. Under a systems approach, to address the identified barriers, their interconnections and the nature of mutual interdependence must be considered. Barrier analysis suggests that limited research and development activities and limited technological demonstration of energy efficiency also need appropriate attention from line ministries, such as those responsible for industry, buildings, transport and relevant departments and not only the power and energy ministries. Simultaneously, focus should be placed on low electricity prices, which reduces motivation for change from end users, limited financial incentives and unpredictable energy prices, as they make it more difficult to implement energy efficiency measures. Institutional arrangements need to be in place to generate information and create awareness among end users, financiers and industrialists about the benefits of energy-efficient technologies. Institutional inefficiency, such as complexity of collaboration, poor association with energy service companies and lack of influence in energy management practices also need to be addressed by the government.

To achieve 24/7 access to modern energy services, the most important actions are to develop an accurate database for providing reliable demand estimates and encourage disclosures; create a political atmosphere with minimized intervention and long-term policy certainty; reform the highly centralized non-transparent bureaucratic system of policymaking under which constructive stakeholder's participation is absent; scrap inefficient policies, such as the continuation of power generation from an ad hoc policy favouring high-cost and inefficient quick rental power plants or captive power generation; and communicate a clear policy message to reconcile power sector development and climate change mitigation targets. Sequentially, such actions would help to overcome such barriers, such as limited exploration and infrastructure related to primary energy, inability to offer affordable and reliable grid power due to costlier petroleum and LNG imports, increased use of costly liquid fuel-based generation, and more emission intensive oil-based power generation. Six autonomous barriers also deserve equal attention: (1) institutional inefficiency,. such as delayed policy implementation, lack of coordination between generation, transmission and distribution; (2) the complex administrative environment and institutional corruption, such as illegal supply connection of gas and electricity, and bribes to tamper meters in urban areas; (3) inappropriate tariff policies, such as irrational energy subsidies and inefficient pricing structure and the absence of long-term energy tariff plans

and market-based tariffs; (4) donor-dependent financing and policy formulation for the energy sector, which results in investment preferencing power generation over transmission and distribution; (5) the lingering problem caused by the low technical efficiency of the grid connected power plants; and (6) inadequate regional cooperation, such as the preference for bilateral policy rather than regional policy, the absence of open market concepts, geopolitical issues and few successes in cross-border electricity trade.

In summary, the analysis shows that the barriers can be overcome through various targeted policy and regulatory mechanisms. By making room for new institutional arrangements and the strategic role of local experts, stakeholders, such as manufacturers, businesses and users can create a sociopolitical environment that makes it possible to break the current interlinked chain of barriers. Simultaneous supplementary efforts, such as provision of capacity-building, creation of a database for both the demand and supply sides and improvement in coordination across institutions, could also be highly beneficial.

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CHAPTER 22

Critical infrastructure resilience in Eastern Economic Corridor of Thailand—a review

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1. Introduction

Critical infrastructures are the backbone of modern and interconnected economies, and disruption of these infrastructures can cause substantial economic damage (OECD, 2019). Any infrastructure is considered critical when it is of major importance to the functioning of modern societies and any failure to such systems can lead to sustained disruption in the overall system.

Critical infrastructure is a complex system that facilitates provision of important services required for functioning of the society, and modern economies. These systems are designed to withstand external shocks and threats that may cause interruption of its functioning and service delivery. Although these systems are designed with utmost planning, precision still faces the potential of risk from natural hazards, technical mishaps, and cyberattacks. This, in turn, depending on the intensity and cause of disruption may lead to failure of services provided by critical infrastructure systems (Rehak, Senovsky, & Slivkova, 2018). Therefore, to safeguard service delivery systems from impending risks, risk management efforts are needed to strengthen resilience of critical infrastructure.

Thailand is placed as a center of economic growth in the South-East Asian region. The economic growth of the country is propelled by the contribution of export-oriented manufacturing, and tourism. The Eastern Economic Corridor (EEC) is a special development zone situated in the coastal area of Chonburi, Rayong, and Chachoengsao provinces of Thailand. The EEC has several major infrastructures as well as poised to attract multiple infrastructure development projects. The EEC is Thailand's

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most growing coastal city due to efforts of the eastern seaboard development in the past and provincial-based development policy through the Eastern Special Development Zone Act, 2018 (Ministry of Natural Resources and Environment, 2018). These policy measures purposes EEC to serve as a regulatory sandbox that boosts the country's competitiveness for the next decade and provide opportunity for critical infrastructure investment especially in transport and logistics network of roads, rail, ships, and air that connects Bangkok and the rest of the EEC (Pootrakool, 2016).

It is an indisputable fact that the interrelationships between infrastructure, urban system, and hazards in the urban disaster continuum are inseparable. Rising urbanization, complexity, the interconnectedness of critical infrastructures, and impending coastal hazards make the EEC a hotspot of potential future risks. The region is also prone to various hazards that include flood, cyclone, tsunami, and coastal erosion. These hazards pose a serious threat to the existing infrastructures including critical infrastructure in the coastal areas mostly, along the Chonburi and Rayong provinces of Thailand. Concerted efforts to assess the complex nature of risk, especially for critical infrastructure systems become prerogative for risk reduction and resilience measures in the EEC region.

This paper is an outcome of the work carried out under the Coalition for Disaster Resilient Infrastructure (CDRI) Fellowship by a team of researchers from the Asian Institute of Technology, Thailand. The paper provides a summary, and analysis of the literature review on the key concepts of critical infrastructure, risk assessment from major natural hazards, and resilience approaches for critical infrastructure. Further, these concepts are cross-analyzed for various critical infrastructures of the EEC. Thus, understanding EEC's hazard potential and development pattern and how resilience of the infrastructure is considered in the broader EEC development process makes this research important for EEC planning and resilience building efforts.

2. Eastern Economic Corridor

The EEC is a special economic zone being developed in the South-East part facing the Gulf of Thailand. EEC is spread over 13,266 km^2 and comprises three main provinces of Chachoengsao, Chonburi, and Rayong. The EEC establishment was announced formally on January 17, 2017 at the direction of the National Council of Peace and Order. The first law on EEC provided the legal support for the development of various institutions,

and infrastructure in the area (Eastern Special Development Zone Act, 2018). The EEC is being developed on the former eastern seaboard to become a major development area with several infrastructure projects. The development work has led to an increase in economic activities and population growth in the region. The strategic plan of EEC aims for substantial changes in both physical and social growth to boost the country's competitiveness for economic prosperity (Tontisirin & Anantsuksomsri, 2021).

3. Hazard profile of EEC

The EEC, like many coastal cities in South-East Asia, faces a wide range of natural hazards based on geographical characteristics (Pleerux, 2013). Coupled with natural hazards are other accelerators pushing the EEC to be more vulnerable that create adverse impacts on the coastal systems and various stresses such as land-use change, pollution, and tourism, among others. One of the most recurring hazard observed in EEC is flood. The flooding problem in the downstream areas of EEC especially in the Bang Pakong River Basin and the Eastern Coast Basin is prominent (Wacharasin, 2018). At the same time, Chonburi and Rayong are mildly prone to other meteorological hazards, especiallly cyclones. In addition, coastal erosion is another major problem facing the EEC area. The current average erosion level in the area is 1−5 m per year, even after soft and hard measures taken by the administration (Ministry of Natural Resources and Environment, 2018).

4. Critical infrastructure

There is no universally accepted definition for critical infrastructure. Countries, regional, and multilateral organizations have adopted their definitions for critical infrastructure. The UNISDR terminology on Disaster Risk Reduction provides a broader definition of critical facilities as "the primary physical structures, technical facilities, and systems which are socially, economically or operationally essential to the functioning of a society or community, both in routine circumstances and in the extreme circumstances of an emergency" (UNISDR, 2009). Organization for Economic Co-operation and Development (OECD) defines critical infrastructures as "the hubs, nodes, and networks of a complex web of interconnectedness and interdependencies, therefore, failure or disruption

of one critical infrastructure can have far-reaching consequences to other sectors, and/or locations" (OECD, 2011). In the definition, UNISDR considers critical facilities as structures, and systems essential for the functioning of society whereas, OECD defines critical infrastructure in terms of its properties such as nodes, networks, and interconnectedness.

Critical infrastructure is defined differently in countries around the world, similarly, sectors that are considered critical, also vary from country to country. In Canada, critical infrastructure includes "processes, systems, facilities, technologies, networks, assets and services important to health, safety, security or economic well-being" (Government of Canada, 2009). Canada's critical infrastructure comprises energy and utilities, finance, food, transportation, government, ICT, health, water, safety, and manufacturing (Government of Canada, 2009). Although definitions of critical infrastructure vary, countries and organizations agree that critical infrastructure includes both physical aspects (facilities, equipment, networks) and key services (health care, safety, etc.), and interruption of these elements and services would threaten society and the state (OECD, 2019). These systems provide critical services to society, but their declining condition and performance inconvenience people and represent disaster risks to communities.

As discussed in the previous section, countries define critical infrastructure based on their priorities and parameters, and critical infrastructure sectors vary in each country, although most consider electric power, natural gas and oil, telecommunications, transportation, banking and finance, water supply systems, emergency services, and government functions (Ouyang, 2014).

An infrastructure is considered critical based on the criticality factor. Criticality is defined as "a relative measure of the importance of a given infrastructure in terms of the impact of its disruption or functional failure on the security of supply, i.e., providing society with important goods and services" (Federal Republic of Germany, 2009). The criticality factor also differs from one organization to another. The European infrastructure is evaluated by its cross-border effect, which determines if an incident could affect two or more member states. The European Council adopted the energy and transport sectors as European Critical Infrastructure in 2008 (European Commission, 2008). In addition, several sectors, including ICT, water, food, health, financial, public, and legal order and safety, civil administration, chemical and nuclear industry, space, and research, were discussed for addition to the list.

4.1 Critical infrastructure features

Below are some characteristic features of critical infrastructures described by (Kröger, 2008):

(a) Critical infrastructures are designed to satisfy certain social requirements and at the same time shape social change at a much broader and much more complex level.

(b) Critical infrastructure consists of human-made networked systems that function synergistically to produce a continuous flow of service to the customer.

(c) Critical infrastructures are interdependent both physically and through a host of Information Communication Technology (ICT).

(d) Critical infrastructures are also vulnerable to various threats that may include technical, natural, cyber, or contextual; unintended or malicious.

(e) Disruption of critical infrastructure may cause cascading impact, and even normal service interruption can cost a few percentages of the Gross Domestic Product (GDP).

(f) Critical infrastructures have no single owner or regulator or operator and their operating environment is based on different goals.

4.2 Critical infrastructure interdependency

Interdependency is a an important feature of critical infrastructure (Little, 2004). Theoretically, interdependency is a bidirectional relation between two infrastructures in which the state of one infrastructure influences or correlates to the state of other infrastructure (Rinaldi et al., 2001). Fig. 22.1 shows the interdependency of the critical infrastructure (power sector) described by Rinaldi et al. (2001).

In a complex system of the infrastructure network, infrastructures are connected at multiple nodes through different mechanisms as a system of systems. Interdependency among infrastructure systems varies widely and each has its characteristics and effects on infrastructure. The infrastructure interdependency is further classified into physical interdependency, geographic interdependency, and logical interdependency.

4.3 Risk assessment of critical infrastructure

Interconnected supply chain, technical, and financial networks increase critical infrastructure risk (Little, 2004). Any shock or disruption to critical infrastructure may cut across several sectors and borders and could reflect

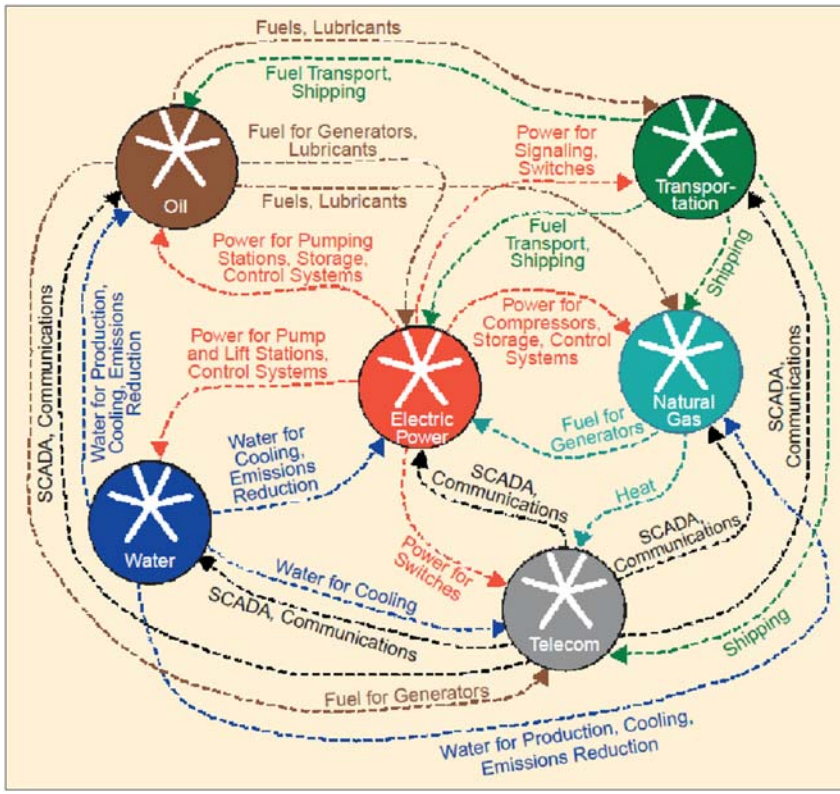

Figure 22.1 Critical infrastructure interdependency. *(Source: Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies.* IEEE Control Systems Magazine*,* 21*(6), 11–25. https://doi.org/10.1109/37.969131.)*

globally (OECD, 2019). Recent incidents of critical infrastructure disruption such as the Chile earthquake (2010), Great East Japan Earthquake (2011), Superstorm Sandy (2012), and Tianjin port explosion (2015) show that interruptions to critical infrastructure and key services can result in severe economic damage and loss of life. The Chile earthquake disrupted transportation and communications. The Great East Japan Earthquake and tsunami damaged Japan's energy sector, reducing electricity generation by 50% and disrupting supply for months. The Superstorm Sandy flooded highways and tunnels in the New York–New Jersey area, disrupting road and rail traffic and electricity for 8.5 million people. The 2015 Tianjin explosion rerouted cargos and tankers for months as the world's sixth largest

harbor. These examples show how disruption of critical infrastructure leads to cascading effects to other sectors. Therefore, protection of these infrastructures becomes paramount, and protection starts with the identification and assessment of risk.

The word *risk* entered into the English language in the 1660s from the Italian word "*riscare*" meaning to navigate among dangerous rocks (Timmerman, 1986). Risk assessment is the process of risk analysis and risk evaluation (ISO/IEC, 2002). Risk analysis is the process for the identification of assets, potential vulnerabilities, and events as well their relationships (Stergiopoulos et al., 2016).

Comprehensive risk assessment is the foundation of critical infrastructure resilience-building. Risk assessment distinguishes risk assessment from effect assessment (Giannopoulos et al., 2012). The risk assessment field for critical infrastructure is not fully standardized, and different risk assessment methods cover different risk assessment aspects (Adar & Wuchner, 2005). It is important to preselect the suitable risk assessment methodology based on critical infrastructure typology and risk sources. Furthermore, several factors shape the risk of critical infrastructures. The International Risk Governance Council (2007) has categorized these factors into natural, technological, system-related, societal, and institutional categories as in Fig. 22.2.

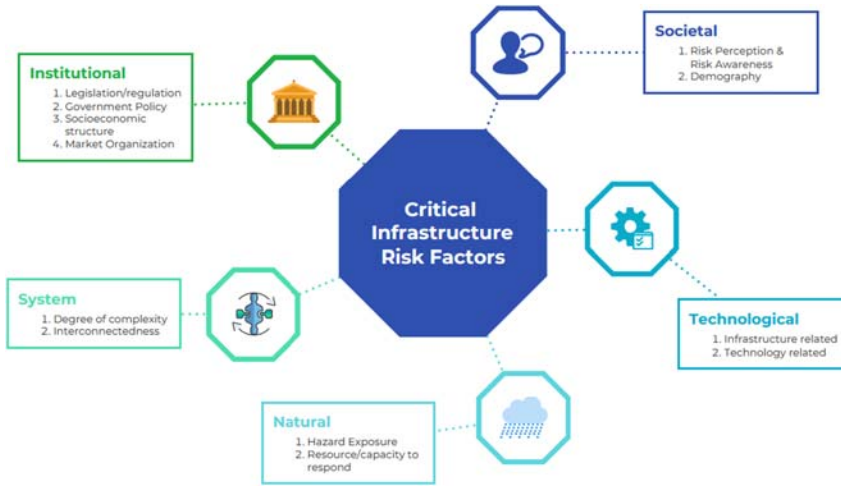

Figure 22.2 Risk factors of critical infrastructure. *(Source: Developed by authors based on IRGC. (2007).* Managing and reducing social vulnerabilities from coupled critical infrastructures. *www.irgc.org.)*

There are several methodologies for risk assessment of critical infrastructure involving identification and classification of hazards or threats, identification of vulnerabilities, exposure, and evaluation of impact. These steps are well-known and established approaches for almost all the risk assessment methodologies. The risk assessment methodology significantly varies on the scope of the methodology, the audience to which it is applied, and their domain of applicability (Giannopoulos et al., 2012).

4.4 Critical infrastructure resilience

According to generally recognized definitions, resilience refers to the level to which critical infrastructure subsystems are internally prepared for emergencies or the ability of these subsystems to perform and sustain their operations when negatively impacted by internal and/or external factors to resist, absorb, accommodate, adapt to, transform, and recover (Alizadeh & Sharifi, 2020). The term *resilience* was first used in the field of ecology for its resistance and stability by Holling (1973). Later, the term was used in other fields such as economics, sociology, psychology, and engineering. In the context of critical infrastructure, resilience is described as the intrinsic preparedness of subsystems to perform and maintain their functions when affected by internal and external shocks and/or threats.

Argonne National Laboratory published "Resilience Measurement Index" in 2013 to define critical infrastructure resilience components (García Reyes, 2013). The report classifies resilience components as preparedness, mitigation, response capabilities, and recovery. Enhancing prevention, absorption, recovery, and adaptation improves critical infrastructure resilience. Fig. 22.3 explains critical infrastructure resilience cycle. The figure depicts existing resilience (black dotted line) is enhanced to a higher level (red dotted line) and difference between these lines implies increased infrastructure resilience (Rehak, Senovsky, & Slivkova, 2018).

Critical infrastructure resilience has been studied extensively by different organizations and governments. European Commission provides extensive information on the critical infrastructure resilience. European Commission has emphasized resilience building measures of critical infrastructure considering its transboundary nature and economic considerations. In 2004, the European Council accentuated protecting essential infrastructures in European Union countries. Furthermore, in 2005, the European Commission adopted a "Green Paper on a European Program for Critical Infrastructure Protection (EPCIP)" to reduce critical infrastructure's

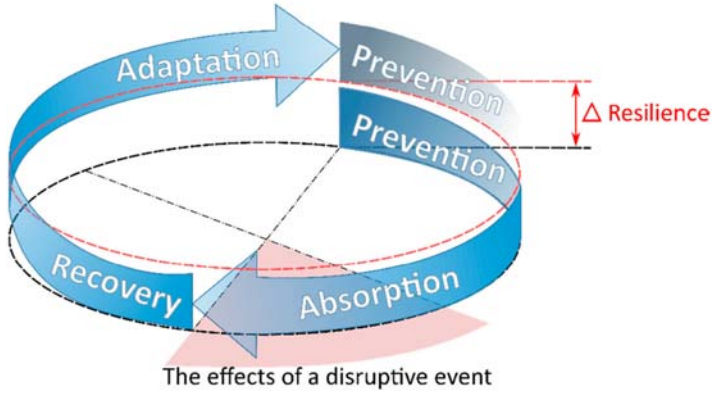

Figure 22.3 Critical infrastructure resilience cycle. *(Source: Rehak, D., Senovsky, P., & Hromada, M. (2018). Analysis of critical infrastructure network. In Z. Chen, M. Dehmer, F. Emmert-Streib, & Y. Shi (Eds.),* Modern and interdisciplinary problems in network science: A translation research perspective *(pp. 143–171).)*

vulnerability to terrorism, natural disasters, and accidents (EC, 2005). The EPCIP underlines that protecting critical infrastructure requires communication, coordination, and cooperation among all stakeholders, including infrastructure owners and operators, regulators, professional bodies, and industry associations (European Commission, 2005).

5. Methodology

This research study firstly analyses existing literature on the critical infrastructure, factors causing risk, and resilience measures for these infrastructures. Further, findings from these efforts are cross-analyzed in the context of critical infrastructure of the Eastern Economic Corridor of Thailand. The finding of the literature analysis is based on a detailed literature survey and synthesis, which was conducted as part of the CDRI fellowship research. The literature survey and analysis involved investigation of journal articles, reports, conference articles, and related books in the field of critical infrastructure, risk assessment, and resilience studies. Furthermore, these concepts of critical infrastructure, risk assessment, and resilience measures are briefly discussed and analyzed in the context of EEC of Thailand. Fig. 22.4 shows the research framework adopted for this paper.

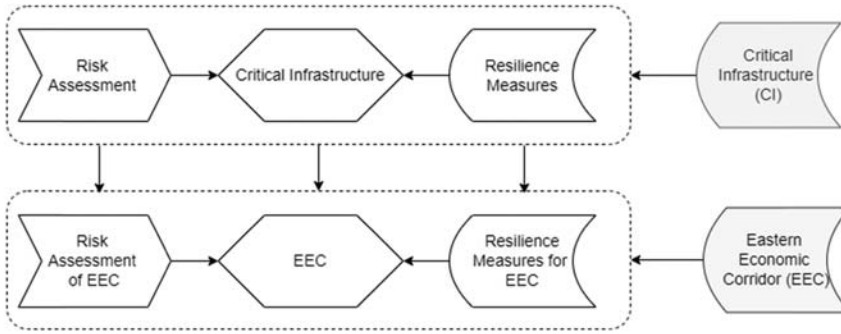

Figure 22.4 Research framework. *(Source: Authors.)*

6. Analysis and results

6.1 Critical infrastructure and EEC

The government of Thailand notified the "Cybersecurity Act" in May 2019. The Act aims to maintain cybersecurity in protecting the Critical Information Infrastructure (CII) of the country. The rationale and necessity of the Act are to prevent and mitigate risk arising from cyber threats that may affect national security, economic, and martial security and public order in the country (Cybersecurity Act, 2019). The National Cyber Security Council (NCSC) of Thailand issued a CII notification that became effective from August 2021. The CII notification considers seven sectors under the purview of CII protection that includes national security; important public services; banking and finance; information technology and telecommunications; transportations and logistics; energy and public utilities; and public health. The notification also prescribes a list of CII regulators, and organizations in charge of regulating and supervising the security of each CII organization. The Cybersecurity Act and CII notification primarily focus on the protection from cyber threats to the identified critical information infrastructures. A holistic approach to consider resilience measures for other threats, hazards, and risks is required to be formulated.

The infrastructure development in the EEC focuses on developing transportation infrastructure including port, airport, road, and high-speed rail networks as well as, diversified industrial corridors. The EEC's objective is to be a model of development in line with Thailand's 4.0 policy. The current infrastructure development projects in EEC may be classified into five categories.

(a) Transportation and logistics infrastructure projects encompass improvements to all modes of transportation; road, railway, seaport, and airport. Fig. 22.5 shows the network of roads, and railways, as well as airports in the EEC area.

(b) Urban redevelopment and rehabilitation projects and new town development have been focused on emerging hybrid developments to create a future economy that supports diverse industries and fosters liveability.

(c) Public utility and facility development projects are more functional and comprehensive, with new developments enabling growth in activity and people wellbeing. Figs. 22.6 and 22.7 have mapped health facilities covering hospitals and health centers as well as educational institutions (universities and schools), respectively.

(d) Digital infrastructure development projects focus on various types of infrastructure; smart poles, advanced big data centers, Internet of Things (IoT), 5G testbeds, and smart cities.

(e) The proposed restoration of coastal and natural resources initiatives prioritizes ecological integrity by protecting critical components such as watershed forests, natural water sources, coastal areas, and mangrove forests.

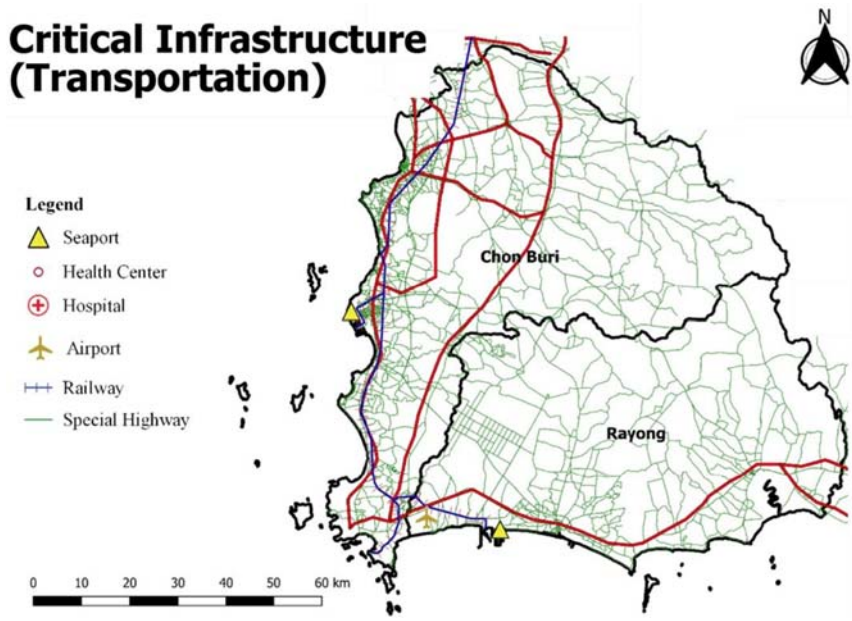

Figure 22.5 Transportation infrastructure in Chonburi and Rayong provinces. *(Source: Authors.)*

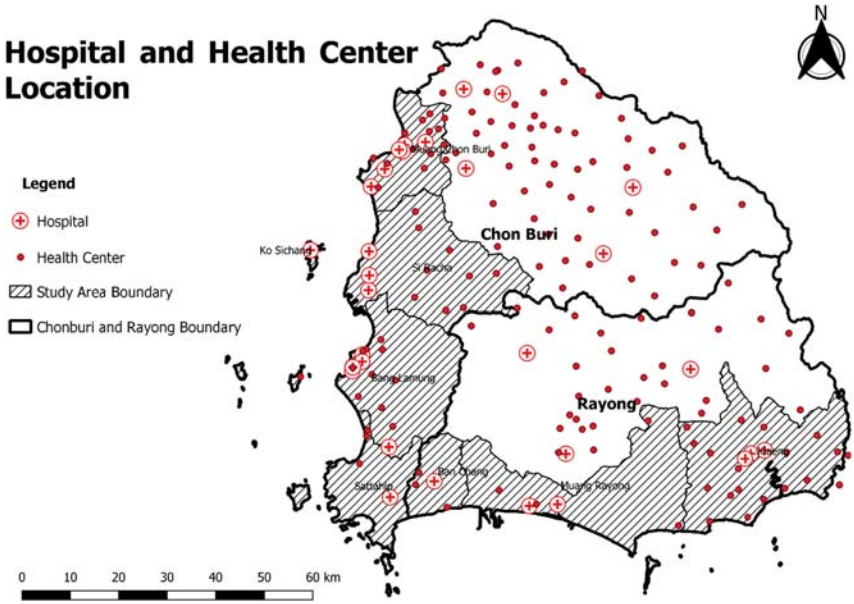

Figure 22.6 Location of hospitals and health centers in Chonburi and Rayong provinces. *(Source: Authors.)*

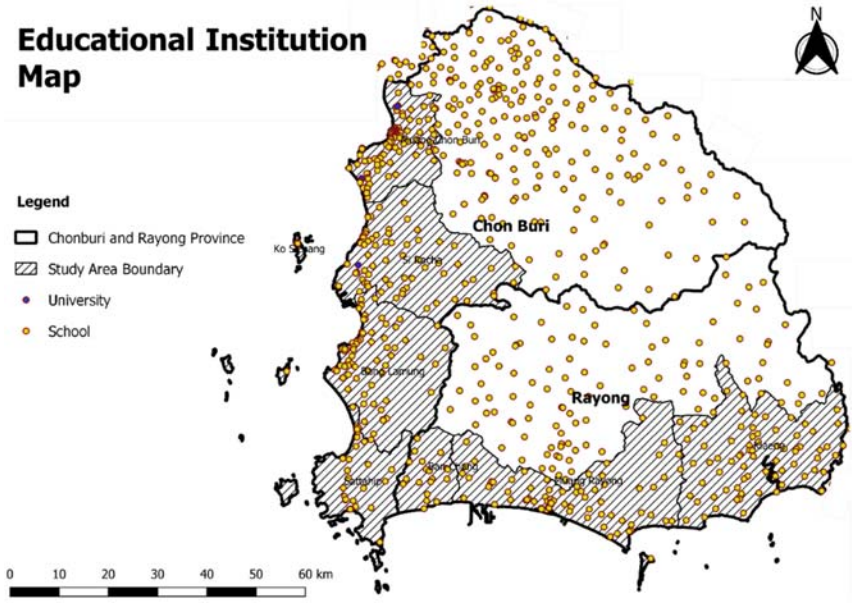

Figure 22.7 Location of educational institutions in Chonburi and Rayong provinces. *(Source: Authors.)*

6.2 Risks of Eastern Economic Corridor

Climate change and coastal hazards such as storm surge, sea-level rise, and flooding can cause risk to several critical infrastructures located in the coastal areas of Thailand. The EEC area faces a wide range of hazards based on geographical characteristics. Coupled with the accelerators pushing the EEC to be more vulnerable to multi-hazards such as climate change, it has increased land and sea surface temperatures and sea-level rises that create adverse impacts on the coastal systems and various stresses such as land-use change, pollution, and tourism, among others. Briefly, potential hazards in this region have been listed below.

6.2.1 Hydrological hazards

Areas under threat from riverine floods and coastal floods due to the increased severity of coastal storms are found in Sriracha and Sattahip municipalities and Pattaya City. The impacts of coastal flood risk on critical infrastructures have appeared, such as damaged coastal roads, offshore structures, and onshore properties by coastal inundation because of high tides from the sea in the area adjacent to the beach.

6.2.2 Meteorological hazards

Compared to other locations, Chonburi and Rayong are less vulnerable to meteorological hazards, particularly cyclones in coastal areas. Regularly, only minor storms affected the maritime sailing of fishing boats. However, moderate to severe drought is prevalent in the hinterland.

6.2.3 Coastal erosion

Chonburi and Rayong are a result of both wind and wave action and anthropogenic activities such as coastal construction and sand mining. The erosion rate can be up to 3–5 m/year in some areas namely, Klongtamru, Laem Chabang, Banglamung, Na Chom Tien, Bangsaray, Sattahip, Plutaleung, and Samaesan.

6.2.4 Technological hazards

EEC is home to industrial estates, economic activities, and urbanization. Such efforts make the EEC vulnerable to technological risks. It has been represented in chemical spills, contamination, machinery explosions or fires, gas leaks, toxic or pollutant releases, and transport accidents (land and water).

Table 22.1 Disaster record in the EEC Region (Chonburi and Rayong Provinces).

Disaster	Chonburi	Rayong
Flood	6 floods in Meung Chonburi, Sattahip, Bang Lamung, and Phanat Nikhom districts.	10 floods in Meung Rayong, Klaeng, and Khao Chamao districts.
Drought	2 droughts in Meung Chonburi, Koh Si Chang, Si Racha, and Phanat Nikhom districts.	6 droughts in Baan hang, Pluak daeng, and Wnag Chan districts.
Windstorms	5 storms.	7 storms
Coastal erosion	Severe in Meung Chonburi, Bang Lamung, and Sattahip districts.	Severe in Ban Chang, Meung Rayong, and Klaeng districts.

Source: Department of Disaster Prevention and Mitigation.

The statistics of natural disasters in the EEC are shown in Table 22.1, which consists of floods, drought, and storms for the period 2006–2011.

6.3 Resilience measures for Eastern Economic Corridor

The mission statement of the EEC says, "determine the optimal use of land in accordance with the area's potential, sustainable development principles, and ensure new development is modernized, safe, and supportive of business activities according to the international standard."

The EEC Master Plan is the empirical evidence for implementation of development, investment, improvement, and resolving existing challenges in the EEC. Water-related planning is the most critical issue, from allocating water resources to utilizing each economic sector, drought management, flood prevention and mitigation, coastal management, and conservation of forests and reserves. Moreover, those plans also consider how to deal with potential emergencies, such as technological hazards or manmade hazards, through improvements and infrastructure developments to mitigate potential uncertainties. These proposed and ongoing initiatives do consider Green Resilient and Inclusive Development (GRID) approach for infrastructure development. Several of the coastal and town planning development work incorporated nature-based solutions to mitigate the effects of hazards through urban planning and design, including resilience strategies.

Along with the team's field survey, it was found that the EEC was highly aware of the impact of disaster risks due to community

concentration, economic sources, and critical infrastructure located in coastal areas. Figs. 22.8–22.13 illustrate examples of projects of both soft and hard mitigation measures in the area, such as the construction of breakwaters in the Map Ta Phut coast that has been affected by coastal erosion, seawall reconstruction at Queen Savang Vadhana Memorial Hospital affected by sea-level changes and coastal storms, riprap construction at Bangsaen beach which is a key tourist spot that protects previously damaged coastal roads from coastal erosion, the construction and establishment of emergency facilities to cover the entire EEC (e.g., DPMCs,

Figure 22.8 Breakwaters along Rayong coast.

Figure 22.9 Sea wall at Queen Savang Vadhana Memorial Hospital, Chonburi.

Figure 22.10 Riprap along Bangsaen beach.

Figure 22.11 U-Tapao Airport with flood-proof design.

Figure 22.12 Ao Udon Community Center serves as emergency shelter.

Figure 22.13 DPMC LCP which works closely with Laem Chabang port.

temporary shelters, and hospitals), and risk-proof design of new facilities (e.g., U-Tapao Airport Laem Chabang Port Map Ta Phut pier land transport network).

7. Conclusion

Thailand encourages investments to upgrade industries and increase competitiveness, enabling the economy to grow. The government of Thailand notified the development of EEC as a major infrastructure development zone in the Chonburi, Rayong, and Chachoengsao provinces. High economic activity has led to massive infrastructure development in the region. At the same time, geographical location, hazard potential, increasing population density, and huge infrastructure development make EEC a potential risk zone in the country. Existing, and planned critical infrastructure are under threat of various risks induced by natural hazards, industrial accidents, and cyberattacks. For the critical infrastructure sector, disasters lead to ripple and cascading impacts on other key sectors of society. To minimize the ripple effect on key economic and social sectors of the economy, risk mitigation and management approaches are required to be implemented. Risk mitigation and management starts with the risk assessment as well as identification of critical infrastructure. Furthermore, identification of the critical infrastructure sector is a challenging task. Criticality criteria play an important role in identifying infrastructure as critical infrastructure. Similarly, the complex and interdependent nature of critical infrastructure systems make the risk assessment process cumbersome.

Thailand considers seven sectors under the purview of Critical Information Infrastructure. The Cybersecurity Act 2019 as well as related policies and regulations prioritize protecting these sectors from cyber threats. However, risks arising from non-cyber threats to critical infrastructure systems need attention. It is also gathered that critical infrastructure is designed according to the concept of sustainability and resilience, and hydrometeorological hazards are the biggest problem to the critical infrastructure systems in the EEC. Therefore, identifying, and assessing the risk arising from different threats and strengthening resilience measures for critical infrastructure sectors become of paramount importance for the country. Further, a systematic approach for risk assessment, establishing a mechanism with a suitable policy framework, as well as strengthening resilience measures considering future threats is important for critical infrastructure in Thailand.

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Conflicts of interest

The authors declare no conflict of interest.

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Carbon Footprint and Economic Analysis of China's Ammonia Energy

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Abstract:

Ammonia energy is a widely used, green and low-carbon new type of clean energy, which has outstanding advantages over hydrogen energy in terms of safety, energy intensity, easy-to-storage and transport, and many other aspects. The application of ammonia energy in transportation, power, chemical and other sectors in China is still in its infancy, but the related carbon footprint research has received much attention. This study conducted a step-by-step life cycle carbon footprint analysis of China's ammonia energy's full industrial chain under application scenarios such as hydrogen refueling stations, ammonia fuel supply stations, and power plants, and focus on analyzing the carbon emission level of ammonia energy used in the scenario of transportation fuel and power sector. The research results show that, from the perspective of different technology routs, in all scenarios, the carbon dioxide emissions of ammonia energy in the whole life cycle of the electrolyzed water hydrogen production HB (Haber Bosch process) synthetic ammonia liquid ammonia vehicle route are the highest, more than 600 $gCO_{2,eq}$/MJ; hydrogen production from renewable energy electrolyzed water - HB synthetic ammonia - pipeline transmission route has the lowest carbon dioxide emission in the whole life cycle of ammonia energy, which is lower than 40 $gCO_{2,eq}$/MJ. For each stage, the fuel production stage accounts for the highest proportion of carbon footprint in all stages of production, storage and application of various ammonia production technology pathway, except for the renewable energy electrolysis ammonia production pathway. From the perspective of influencing factors, the power consumption level and its carbon emission factor in each stage of hydrogen production, ammonia generation and ammonia cracking for hydrogen production play an important role in the carbon footprint of the whole industrial chain of ammonia energy production, storage and utilization. From the perspective of application scenarios, in the scenarios of chemical plants, steel plants, and power plants, due to the short transportation distance and low energy consumption for storage and transportation, the carbon dioxide emissions throughout the full life cycle of 1MJ ammonia energy are relatively low. From the perspective of application scenarios, in the field of transportation, the green ammonia and blue ammonia technology pathway has the advantage of significantly reducing the carbon footprint (more than 80%) compared with traditional fuels.

This research also conducted a comprehensive technological and economic analysis of the entire ammonia energy supply chain, including hydrogen production, ammonia synthesis, and ammonia transportation, by establishing an ammonia energy supply chain technological and economic analysis model and database.

Based on current and future key parameters, different technological pathways were analyzed, revealing significant differences in the levelized costs of various technological routes within China's ammonia energy supply chain. The cost competitiveness of green ammonia in applications such as transportation is currently suboptimal but is expected to demonstrate favorable economic performance in specific sub-sectors by the period 2030-2035. The main conclusions are as follows: (1) There are significant differences in the levelized costs among different technological routes for ammonia energy production and storage. On the ammonia synthesis side, the levelized costs of traditional fossil energy-based hydrogen and ammonia production are noticeably lower than those of renewable energy-based electrolysis and electrolysis-HB synthesis of ammonia. (2) In terms of ammonia synthesis, the levelized costs for various ammonia production technologies range from 2.69 to 10.95 yuan/kg. (3) On the ammonia transportation and application side, there are significant cost differences among various transportation technologies and application scenarios, with overall costs ranging from 0.14 to 1.65 yuan/kg.

Key words: Ammonia energy; Carbon footprint; Cost analysis; Application scenario

Chapter 1: Carbon footprint analysis of the entire industry chain for ammonia energy production, storage, and transportation in China, targeting different application scenarios

It is well known that controlling greenhouse gas (GHG) emissions is at the core of low-carbon development. Greenhouse gases refer to gaseous components in the atmosphere, both naturally occurring and generated by human activities, capable of absorbing and emitting radiation within the infrared spectrum from the Earth's surface, atmosphere, and cloud layers (GB/T 32150-2015) [1], . These primarily include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6), with the last five gases converted into CO_2 equivalents based on their 100-year global warming potential. Greenhouse gas emissions are often referred to as carbon emissions, and unless specified otherwise, "carbon emissions" in this text denote greenhouse gas emissions.

Product Carbon Footprint (PCF) is defined in the international standard ISO 14067 (first edition, August 2018), "Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification," as the sum of greenhouse gas emissions and removals in a product system, expressed in terms of carbon dioxide equivalents. This is based on a life cycle assessment using the single impact category of climate change. Here, the life cycle (LC) refers to a series of interconnected stages in the product system, from extracting raw materials from the natural environment or natural resources to final disposal (GB/T 24040-2008) [3] . Life Cycle Assessment (LCA) is the compilation and evaluation of inputs, outputs, and potential environmental impacts throughout the life cycle of a product system (GB/T 24044-2008) [4] In comparison to accounting methods that only include emissions from certain production processes, carbon footprint calculations encompass the entire upstream and downstream processes of a product.

The development of hydrogen and ammonia energy is gaining increasing attention and has become a crucial technological direction. Hydrogen faces obstacles in large-scale applications due to safety concerns, low ignition points, flammability, and difficulties in storage and transportation. On the other hand, ammonia fuel, being a carbon-free compound, does not produce CO_2 during combustion, emitting only water, nitrogen, and small amounts of nitrogen oxides. It serves as a new green energy source that can substitute fossil fuels. Additionally, ammonia is a hydrogen-rich carrier, with a hydrogen content of up to 17.6%, making it suitable for hydrogen storage and transportation. It boasts high energy density, safety, ease of compression and liquefaction, among other advantages [5].

Ammonia has diverse applications, including its use in fertilizers and fuels across various fields. Currently, countries like Japan have undertaken research and development applications of ammonia as a fuel, focusing on areas such as gas turbines, internal combustion engines, and fuel cells. China, being a major producer of synthetic ammonia with an annual output of approximately 50 million tons, accounting for one-third of the world's total production [6], has witnessed a shift in ammonia consumption trends. While the consumption of synthetic ammonia in the fertilizer sector is declining, its use in non-fertilizer sectors is increasing, particularly in environmental protection, new materials, and the chemical industry. Overall, synthetic ammonia consumption shows resilient support, with the scale expected to continue growing until 2030. It is estimated that domestic demand for synthetic ammonia will reach approximately 64 million tons per year by 2025 [7].

The raw material structure for synthetic ammonia production in China differs significantly from international practices. Internationally, natural gas is the primary production material for ammonia, while in China, coal accounts for 77% of the total production capacity. The production of ammonia in China mainly utilizes coal gasification-Haber-Bosch (HB) technology, involving the production of hydrogen through coal gasification for hydrogen gas and nitrogen obtained through air separation for nitrogen gas. Ammonia synthesis is then achieved by introducing a catalyst under high-temperature and high-pressure conditions through the HB process. Currently, the storage and transportation of ammonia primarily rely on liquid ammonia tank truck technology, with liquefied ammonia transported via trucks to application scenarios such as chemical plants for the production of fertilizers and refrigerants [7].

At present, approximately 80% of ammonia applications in China are concentrated in the fertilizer sector, and research on its use as a fuel is still in its early stages [8]. Existing studies indicate that ammonia exhibits outstanding performance in various fields, such as transportation and power generation. Xia et al. (2021) [1] have analyzed the specific applications of different ammonia fuel mixtures in the transportation sector, providing a systematic outlook for the development of ammonia fuel in China's carbon-neutral context. Xu et al. (2019) [10] have explored ammonia's application as an engine fuel and in fuel cells for transportation, highlighting its advantages and limitations as a vehicle energy source, advocating for accelerated research and application of ammonia fuel. Gao (2022) [11] ducted on the combustion technology of ammonia fuel under zero-carbon electricity, outlining its significant role in various fields, including gas turbines, internal combustion engines, fuel cells, and boilers.

In general, existing research predominantly focuses on the prospective applications of ammonia energy as a fuel in transportation and power generation. However, there is a scarcity of studies analyzing the carbon emissions at different stages, including production, storage, transportation, and overall industry chain carbon footprint, across various application scenarios of ammonia energy. From international research perspectives, Chisalita et al. (2020) [12]estimated that the carbon dioxide emissions during the ammonia production phase from natural gas reforming were 163 $gCO_{2,eq}$/MJ, while Bicer et al. (2017) [13] calculated the carbon emissions during the ammonia production phase from natural gas reforming-HB synthesis at 108 $gCO_{2,eq}$/MJ. Additionally, they estimated the carbon emissions during the ammonia production phase from coal gasification-HB synthesis to be 172 $gCO_{2,eq}$/MJ. In a domestic study, Liu Tingting et al. (2021) [14] calculated the carbon emissions during ammonia production from coal gasification-HB synthesis to be 223 $gCO_{2,eq}$/MJ. Overall, research data related to the ammonia energy carbon footprint is limited and lacks timeliness.

Therefore, based on the practical conditions of ammonia energy production, storage, and transportation in China, conducting a comprehensive industry chain carbon footprint calculation that encompasses various application scenarios, including ammonia production, storage, transportation, and utilization, holds both academic and practical significance.

1 Modeling Method

1.1 Computational Framework

The functional unit for the study is set as 1 MJ of ammonia energy, and the conversion is based on the heating value of ammonia, which is 18.6MJ/kg[15]. This study employs the Tsinghua-LCA model [16] to conduct a life cycle assessment. It calculates the greenhouse gas emission intensity, abbreviated as carbon intensity, throughout the entire life cycle of ammonia energy products from raw material acquisition to production and application. This involves a comprehensive analysis of the carbon footprint for the entire industry chain of ammonia energy in China, covering production, storage, transportation, and utilization stages (including hydrogen production, hydrogen transportation, ammonia production, ammonia transportation, and ammonia utilization). The ammonia production stage includes processes such as air separation for nitrogen, synthetic ammonia production, and ammonia gas purification. The ammonia utilization stage encompasses potential processes for ammonia cracking to produce hydrogen.

The study objects include representative ammonia production processes using traditional fossil energy sources, such as coal gasification-HB synthesized ammonia, natural gas reforming-HB synthesized ammonia, and water electrolysis-HB for hydrogen production. It also considers multiple technological pathways, including wind power as a representative renewable energy source for water electrolysis-HB synthesized ammonia. The application scenarios for ammonia energy or its cracking-produced hydrogen mainly include hydrogen refueling stations, hydrogen power generation stations, chemical plants, ammonia fuel supply stations, and ammonia power generation stations. It is worth noting that the current utilization of ammonia in chemical plants is primarily as a raw material rather than a "substance providing energy." Strictly speaking, it is not an "application of energy." However, for the completeness of the research framework and comparability of the analysis results, this study still defines this scenario as a broad "ammonia directly used in chemical plant scenarios."

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The research boundary includes direct emissions and indirect emissions corresponding to various process fuels and transportation fuel usage. The carbon emissions from wind and photovoltaic power generation include indirect emissions from relevant stages of equipment manufacturing, installation, and maintenance.

1.2 Model Introduction

The Tsinghua-LCA model consists of two progressively hierarchical components: (1) a foundational platform for calculating the LCA (Life Cycle Assessment) energy and GHG (Greenhouse Gas) emission intensity of China's

major end-use energy sources (hereinafter referred to as the foundational platform), and (2) an analytical program for micro-level calculations of LCA energy consumption and GHG emissions for specific fuel pathways (hereinafter referred to as the analytical program) within these routes. The foundational platform employs an iterative computational method based on the computer EXCEL software, enabling the calculation of the full life cycle (or upstream stages) fossil energy and GHG emission intensity data inventory for China's major end-use energy sources. The analytical program, based on the subdivision of fuel route sub-stages and corresponding end-use energy consumption conditions, combined with the life cycle intensity data inventory of end-use energy, can calculate the full life cycle energy consumption and GHG emissions for specific fuel routes using a self-developed program.

In the model, the End-Use Energy Full Life Cycle Fossil Energy Intensity (EF_{LCA}) is defined as the total consumption of primary fossil energy, including raw material inputs, per 1 MJ of end-use energy obtained (MJ/MJ). The End-Use Energy Full Life Cycle Carbon Emission Intensity (GHG_{LCA}) is defined as the greenhouse gas (GHG) emissions, expressed in grams of CO_2 equivalent, per 1 MJ of end-use energy obtained and utilized (g $CO_{2,eq}$/MJ).

The consideration of primary fossil energy input involves three types: coal, oil, and natural gas (NG). The focus of analysis is on nine types of end-use energy, including coal, oil, natural gas, base fuels, and electricity. The full life cycle is divided into four sub-stages: raw material production, raw material transportation, fuel production, and fuel transportation. In the case of end-use energy, clean coal is obtained by washing and transporting raw coal, while refined natural gas is obtained by pressurizing and transporting original natural gas before being used as end-use energy.

When calculating the full life cycle inventory, the system boundary extends to the direct use of related process fuels and transportation fuels, along with their corresponding LCA energy consumption and GHG emissions. However, activities leading to indirect energy consumption, such as factory infrastructure construction and transportation vehicle manufacturing, are not taken into account.

The corresponding calculation methods are represented by formulas (1) to (4):

$$FE_{LC,j}=\sum_{i=1}^{3} FE_{LC,j,i} \quad (1)$$

$$FE_{LC}=\sum_{z}\sum_{j}\sum_{i}(EN_{m,z,j}PEF_{j,i}) \quad (2)$$

In the formulas provided: FE_{LC} represents the Full Life Cycle Fossil Energy Intensity（MJ/MJ）, which is the fossil energy intensity caused by obtaining and using 1 MJ of fuel. i stands for the type of primary energy source (raw coal, natural gas, crude oil) ,j denotes the type of process fuel (coal, natural gas, gasoline, diesel, fuel oil, electricity), m represents the technological route, z signifies various production, processing, and transportation stages, and $EN_{m,z,j}$ represents the consumption of process fuel j at production stage z（MJ/MJ）. Furthermore, $PEF_{j,i}$ stands for the conversion coefficient between process fuel and primary fossil energy.

$$GHG_{LC}=CO_{2,LC}+25CH_{4,LC}+298N_2O_{LC} \quad (3)$$

$$GHG_{G,Z}=\sum_{z=1}^{4}\sum_{j}^{6} EN_{m,z,j}\cdot(DEC_{G,j}+UEC_{G,j}) \quad (4)$$

GHG_{LC} represents the Full Life Cycle Greenhouse Gas (GHG) Emission Intensity（$gCO_{2,eq}$/MJ）, which is the GHG

emission intensity caused by obtaining and using 1 MJ of fuel. The main consideration is given to three GHGs (CO_2、CH_4、N_2O) ，and they are uniformly converted to CO_2 equivalent based on the global warming potential factors. G denotes the type of GHG emission, including $CO_{2,LC}$、$CH_{4,LC}$、N_2O_{LC}，representing the Full Life Cycle CO_2、CH_4、N_2O emission intensities (g/MJ) respectively. $DEC_{G,j}$represents the direct emission factor, and $UEC_{G,j}$ represents the upstream emission factor.

1.3 Calculation Process

The research, following the calculation process mentioned in section 2.2 for the "analysis program," consists of three steps: 1）Compile Energy Consumption Data for Stages of Hydrogen Production, Hydrogen Transportation, Ammonia Production, Ammonia Transportation, and Ammonia Utilization. 2）Update Full Life Cycle Carbon Intensity Coefficients for End-Use Energy. 3）Calculate Carbon Emission Levels for Each Stage and Summarize to Account for the Overall Carbon Footprint of the Entire Ammonia Industry Chain.

2 Data Compilation

For the carbon emission analysis needs in various stages of hydrogen production, hydrogen transportation, ammonia production, ammonia transportation, and ammonia utilization, this study's data compilation focuses on collecting various energy consumption data for stages including raw material production, raw material transportation, fuel production, fuel transportation, and fuel application. Additionally, there is a focus on updating and organizing the coefficients for the full life cycle carbon intensity of end-use energy.

2.1 Raw Material Production, Raw Material Transportation, and Fuel Production Stages

2.1.1 Coal Gasification-Haber-Bosch Synthesis Ammonia Technology Route

At the current stage, Coal Gasification-Haber-Bosch Synthesis is the most predominant ammonia production technology in China, with a focus on advanced fluidized bed gasification methods.

（1）Raw Material Production Stage

The main consideration is the energy consumption and carbon emissions generated during the production and processing of raw coal. The primary energy consumption for 1 MJ of coal during the coal mining and processing stage is 0.066MJ for coal, 0.003 MJ for oil, and 0.002 MJ for natural gas [17] .

（2）Raw Material Transportation Stage

The primary consideration is the energy consumption and carbon emissions generated during the transportation of raw coal. The primary energy consumption for 1 MJ of coal during the coal transportation stage is 0.02 MJ for coal, 0.012 MJ for oil, and 0.001 MJ for natural gas [17].

（3）Fuel Production Stage

The main focus is on the consumption of coal and electricity during the production stage of 1 MJ of ammonia. The consumption for 1 MJ of ammonia production is 1.61 MJ for coal and 0.23 MJ for electricity[18,19] .

2.1.2 Natural Gas Reforming-Haber-Bosch (NGR-HB)

NGR-HB process primarily utilizes natural gas as the hydrogen production feedstock. Additionally, it involves the consumption of some electricity during the reforming and Haber-Bosch (HB) processes.

（1）Raw Material Production Stage

The main focus is on the energy consumption and carbon emissions during the production and processing of natural gas. The primary energy consumption for 1MJ of natural gas is as follows: coal 0.066MJ, oil 0.007MJ, and natural gas 0.145MJ [17].

（2）Raw Material Transportation Stage

The main focus is on the energy consumption and emissions during the transportation of raw natural gas. The primary energy consumption for 1MJ of natural gas during transportation is as follows: coal 0.05MJ, oil 0.012MJ, and natural gas 0.001MJ [17].

（3）Fuel Production Stage

In the Fuel Production Stage, which corresponds to the main process of Natural Gas Reforming in the NGR-HB synthesis of ammonia, the focus is on the consumption of natural gas and electricity. The consumption for the production of 1MJ of ammonia during the fuel production stage is natural gas 1.94MJ and electricity 0.15MJ [20,21].

2.1.3 Hydrogen production by electrolysis of water - HB synthesis of ammonia

The carbon emission analysis of electrolyzing water to produce hydrogen followed by the Haber-Bosch synthesis of ammonia includes two routes: grid electricity electrolyzing water to produce hydrogen and the Haber-Bosch synthesis of ammonia, and renewable energy electricity (represented by wind and photovoltaic power) electrolyzing water to produce hydrogen and the Haber-Bosch synthesis of ammonia. In the grid electricity route, there is significant energy consumption and carbon emissions in the stages of raw material production, raw material transportation, and fuel production, while wind and photovoltaic power have relatively smaller impacts in these stages.

（1）Raw Material Production Stage

Mainly considering the energy consumption and emissions of various power generation technologies. The one-time energy consumption of 1MJ grid electricity in the raw material production stage is 0.158MJ for coal, 0.008MJ for petroleum, and 0.009MJ for natural gas[17].

（2）Raw Material Transportation Stage

Mainly considering the energy consumption and carbon emissions of grid electricity during transportation. The one-time energy consumption of 1MJ grid electricity, used as raw material for hydrogen and ammonia production, in the transportation stage is 0.006MJ for coal, 0.029MJ for petroleum, and 0.002MJ for natural gas[17].

（3）Fuel Production Stage Under the Proton Exchange Membrane (PEM) electrolysis route, the electricity consumption for 1MJ of ammonia is 2.13MJ[22, 23,24].

2.2 Fuel Transportation and Fuel Application Stage

2.2.1 Fuel Transportation Stage

（1）Ammonia Tank Truck

In this method, the produced ammonia gas is compressed and pressurized to a certain pressure level. After that, it is transported to the application site through large ammonia storage tanks using ammonia tank trucks. The energy consumption during the ammonia gas compression process mainly comes from electricity usage. According to Wang Yuegu et al.（2019）[20], the electricity consumption for compression in this stage is 0.18 kWh/kg of ammonia, and the diesel consumption during transportation is 25 L/100 km (for a transport quantity of 9000 kg/vehicle).

（2）Pipeline transportation

This method primarily considers the electricity consumption for compressing ammonia. According to reference [25], the transportation cost for a 2000 km hydrogen pipeline and a 2000 km ammonia pipeline is 6.50 CNY/kg hydrogen and 1.17 CNY/kg hydrogen (equivalent to 0.21 CNY/kg ammonia). Using the energy consumption for transporting hydrogen in a 25 km pipeline from Luoyang to Jiyuan as a reference for ammonia transport in a 750 km liquid ammonia pipeline, the annual transport capacity of this project is 219,700 tons/year, with a compression electricity consumption of 0.18 kWh/kg [26].

（3）Liquid Ammonia Tank Truck

In this method, ammonia is cooled to -33°C to liquefy it, and then it is loaded into liquid ammonia tanks and transported to the application site using tank trucks. The carbon emission analysis for this method mainly considers the energy consumption during liquefaction and fuel consumption during transportation. A tank truck can transport 27,000 kg of liquid ammonia in one trip, consuming 25 L of fuel per 100 km [26].

（4）Liquid Ammonia Ship

For this method, the analysis primarily considers the electricity consumption for liquefying ammonia and the fuel consumption during the ship's operation. Referring to cases studied by Niermann et al. (2019)[26] and Kim et al. （2021[28] , the ship in this study consumes 56 tons of fuel per day (for a carrying capacity of 58,600 tons), with specific data shown in Table 1.

Table.1 Basic parameters of liquid ammonia ship mode

Parameter	Unit	Value
Parameter fuel consumption	Tons/day	56
Speed	km/h	27.78
Liquefaction power consumption	kWh/kg	0.6

（5）Liquid Ammonia Tank Truck

In this method, ammonia is liquefied and stored in liquid ammonia tanks, which are then transported to the designated application site using tank trucks. Referring to the data from Wang Yuegu et al. (2019)[20] , for a tank truck that can transport 10,000 kg of liquid ammonia in one trip, it consumes 25 L of fuel per 100 km. Specific data can be found in Table 2.

Table.2 Basic parameters of liquid ammonia tank car mode

Parameter	Unit	Value
Diesel consumption	L/100km	25
Storage and transportation capacity	kg/车	10000
Liquefaction power consumption	kWh/kg	0.6

2.2.2 Fuel application stage

The analysis primarily focuses on the stage of ammonia cracking to produce hydrogen (if applicable) and the utilization stages of either ammonia or hydrogen gas. Due to the nature of application scenarios such as chemical plants, fuel supply stations, and power plants, if ammonia is directly utilized, this stage does not result in direct carbon emissions. However, if ammonia is transported as a fuel for transportation or electricity to hydrogen refueling stations or hydrogen power plants, it undergoes an ammonia cracking process to produce hydrogen before being utilized. The electricity consumption for the process of cracking 1 kg of ammonia into hydrogen is 3.26 kWh/kg [29].

2.3 The full life cycle carbon intensity coefficients of terminal energy sources

As shown in Table 1, the full life cycle carbon intensity coefficients of China's main terminal energy sources are cited from reference[17]. These intensity inventory data, in conjunction with the terminal energy consumption levels mentioned in Sections 3.1 and 3.2 related to the production, storage, transportation, and utilization stages of ammonia energy, can be used to calculate the full life cycle carbon emissions of ammonia energy, commonly referred to as its carbon footprint. Additionally, based on the study from reference [30], the full life cycle carbon emissions of photovoltaic and wind power, mainly considering indirect carbon emissions from manufacturing, installation, and maintenance of power generation equipment, are 29.2 and 8.6 gCO_2,eq/kWh, respectively.

Table. 1 The Full Life Cycle Fossil Energy Intensity and Carbon Intensity of China's Major Terminal Energy Sources

Project	EF_{LC}	GHG_{LC}
Unit	MJ/MJ	$gCO_{2,eq}$/MJ
Raw coal	1.075	98.6
Original natural gas	1.147	68.1
Crude oil	1.102	79.6
Clean coal	1.090	99.7
Refined natural gas	1.152	69.8
Diesel oil	1.269	93.1
Gasoline	1.278	91.0
Fue oil	1.205	91.4
Power	2.663	237.1

3 The research results and discussion

3.1 Carbon Footprint of Ammonia Energy in Different Application Scenarios

The use of ammonia is becoming increasingly diverse, serving not only as an industrial raw material but also as a fuel for driving the low-carbon development of shipping and transportation industries. Additionally, ammonia is utilized as a fuel in power plants. Therefore, conducting a differentiated analysis of the carbon footprint of ammonia energy in various application scenarios, including hydrogenation stations, ammonia power plants, chemical plants, ammonia fuel supply stations, and hydrogen power plants, is of great significance. In these scenarios, variations exist in the transportation distances of ammonia energy, as well as in whether ammonia is directly utilized or first converted into hydrogen for use.

This study reveals significant differences in the carbon footprint levels of ammonia energy across these diverse application scenarios.

3.1.1 Hydrogen Production from Ammonia for Hydrogenation Station Scenario

We can present the carbon footprint levels of the entire ammonia chain in the hydrogenation station scenario. In this scenario, the distances for maritime shipping and pipeline transport are 1200 km and 750 km, respectively, while other methods have a distance of 130 km [26]. The full lifecycle carbon emissions for the route involving grid electricity electrolysis, HB synthesis of ammonia, transportation of ammonia by liquid ammonia truck, and grid electricity decomposition of ammonia for hydrogen production are the highest, at 657.7 gCO_2eq/MJ of ammonia energy. On the other hand, the route involving wind electricity electrolysis, HB synthesis of ammonia, pipeline transport of ammonia, and photovoltaic electricity decomposition of ammonia for hydrogen production has the lowest full lifecycle carbon emissions, at 18.4 gCO_2eq/MJ of ammonia energy. Overall, the traditional fossil fuel-HB synthesis of ammonia and grid electricity electrolysis-HB synthesis of ammonia routes are relatively high in carbon emissions for the entire chain, while the pathways involving green electricity for hydrogen production, ammonia synthesis, and ammonia decomposition for hydrogen production have the lowest carbon emissions across all stages.

3.1.2 Ammonia Cracking for Hydrogen-Powered Power Plant Scenario

We can present the carbon footprint levels of the entire ammonia chain in the hydrogen-powered power plant scenario. In this scenario, the distance for pipeline transport is 750 km, while other methods have a distance of 2 km [26]. The full lifecycle carbon emissions for the route involving grid electricity electrolysis, HB synthesis of ammonia, pipeline transport of ammonia, and photovoltaic electricity decomposition of ammonia for hydrogen production are the highest, at 657.2 gCO_2eq/MJ of ammonia energy. Conversely, the route involving wind electricity electrolysis, HB synthesis of ammonia, pipeline transport of ammonia, and photovoltaic electricity decomposition of ammonia for hydrogen production has the lowest full lifecycle carbon emissions, at 18.4 gCO_2eq/MJ of ammonia energy. Overall, the traditional fossil fuel-HB synthesis of ammonia and grid electricity electrolysis-HB synthesis of ammonia routes remain relatively high in carbon emissions for the entire chain, while the pathways involving green electricity for hydrogen production, ammonia synthesis, and ammonia decomposition for hydrogen production have the lowest carbon emissions across all stages.

3.1.3 Ammonia directly used for ammonia in chemical plant scenario

We can illustrate the full lifecycle carbon footprint levels of the entire ammonia chain in the chemical plant scenario. In this scenario, the distance for pipeline transport is 750 km, while other methods have a distance of 2 km [26]. Since in this scenario, ammonia is directly utilized without being cracked into hydrogen, the carbon footprint level of the entire lifecycle of ammonia energy is lower than that of the hydrogenation station scenario and hydrogen-powered power plant scenario. Among the various technological routes, the route with the highest total carbon emissions throughout the lifecycle is the grid electricity electrolysis-HB synthesis of ammonia-liquid ammonia tanker route, with a carbon footprint level of 523.3 gCO_2eq/MJ of ammonia energy. The lowest carbon footprint level is observed

in the route involving wind electricity electrolysis-HB synthesis of ammonia-pipeline transport of ammonia, with a carbon footprint level of 12.9 gCO_2eq/MJ of ammonia energy.

3.1.4 Ammonia Used Directly in Ammonia Fuel Supply Station Scenario

We can depict the full lifecycle carbon footprint levels of the entire ammonia chain in the ammonia fuel supply station scenario. In this scenario, the distances for ocean shipping and pipeline transport are 1200 km and 750 km, respectively, while other methods have a distance of 130 km [26]. This scenario is similar to the one where ammonia is directly used in a chemical plant; ammonia is utilized directly without being cracked into hydrogen, resulting in a lower carbon footprint level for the entire lifecycle of ammonia energy compared to the hydrogenation station and hydrogen-powered power plant scenarios. Among the various technological routes, the route with the highest total carbon emissions throughout the lifecycle is the grid electricity electrolysis-HB synthesis of ammonia-liquid ammonia tanker route, with a carbon footprint level of 523.8 gCO_2eq/MJ of ammonia energy. The lowest carbon footprint level is observed in the route involving wind electricity electrolysis-HB synthesis of ammonia-pipeline transport of ammonia, with a carbon footprint level of 12.9 gCO_2eq/MJ of ammonia energy.

3.1.5 Ammonia Used Directly in Ammonia-Powered Power Plant Scenario

We can illustrate the carbon footprint levels of the entire ammonia chain throughout its lifecycle in the scenario where ammonia is directly used in an ammonia-powered power plant. In this scenario, the distances for pipeline transport are 750 km, and for other methods, it is 2 km [26]. With shorter ammonia transport distances and direct utilization without cracking into hydrogen, the carbon footprint level for the entire lifecycle of ammonia energy is lower in this scenario compared to the hydrogenation station and hydrogen-powered power plant scenarios. Among the various technological routes, the route with the highest total carbon emissions throughout the lifecycle is the grid electricity electrolysis-HB synthesis of ammonia-liquid ammonia tanker route, with a carbon footprint level of 523.3 gCO_2eq/MJ of ammonia energy. The lowest carbon footprint level is observed in the route involving wind electricity electrolysis-HB synthesis of ammonia-pipeline transport, with a carbon footprint level of 12.9 gCO_2eq/MJ of ammonia energy.

3.1.6 Discussion on the Impact of Ammonia Transport Distance on Carbon Footprint

The energy consumption during the ammonia transport stage primarily includes the energy used for oil and gas transportation and the electricity consumption for ammonia liquefaction and compression. The corresponding carbon emissions vary with the change in transport distance. Under the assumption of not considering other influencing factors, there is a significant difference in carbon emission levels for different transport modes at different transport distances. Within a transport range of 2500 km, pipeline transport and gas-ammonia truck transport, both using gaseous form transport, exhibit lower carbon emission levels. On the other hand, liquid ammonia truck transport, liquid ammonia tanker transport, and maritime transport, which use liquid form transport, have higher carbon emission levels. For these three transport modes, the 1500 km transport distance is roughly the equilibrium point for pipeline transport and gas-ammonia truck transport, with the shorter distance favoring the low-carbon advantage of pipeline transport. Additionally, for transport distances exceeding 2500 km, maritime transport demonstrates a relatively lower impact on the carbon footprint.

3.1.7 Comparison with Similar Research Results

Several stages of some routes in this study have corresponding research results in similar studies conducted domestically and internationally, and overall, the results are quite similar. Chisalita et al. (2020) [12] calculated the lifecycle carbon dioxide emissions during the natural gas reforming and ammonia synthesis stage to be 163 gCO_2,eq/MJ. Bicer et al. (2017) [13] estimated the lifecycle carbon emissions during natural gas reforming and HB synthesis ammonia stage to be 108 gCO_2,eq/MJ. These values are close to the result in this study for the natural gas reforming-HB synthesis ammonia stage, which is 141 gCO_2,eq/MJ. Liu et al. (2021) [14], in their research on the lifecycle carbon emissions of coal gasification-HB synthesis ammonia, reported a value of 223 gCO_2,eq/MJ. Bicer et al. (2017) [13] reported a result of 172 gCO_2,eq/MJ for the lifecycle carbon emissions of coal gasification-HB synthesis ammonia. These values are also in close proximity to the result in this study, which is 181 gCO_2,eq/MJ.

3.2 Discussion on the Carbon Emission Situation of Blue Ammonia Technology

Research indicates that coupling Carbon Capture and Storage (CCS) technology is a possible solution to reduce CO_2 emissions in the traditional fossil fuel-based hydrogen/ammonia production processes. For example, the Coal Gasification-Hydrogen Production+CCS+HB Synthesis Ammonia technology can capture and store CO_2 during the hydrogen production phase, which is later compressed and transported to a designated location. Calculations show that the CO_2 emissions during the hydrogen production phase of coal gasification-ammonia synthesis are 20 kgCO_2/kgH2. When CCS technology is integrated (assuming a compression electricity consumption of 0.062 kWh/kg CO_2), the CO_2 emissions during the hydrogen production phase for blue ammonia are reduced to 1.5 kgCO_2/kgH2, representing a 92.5% reduction compared to the former [31]. Correspondingly, the route of producing hydrogen using coal with CCUS (Carbon Capture, Utilization, and Storage) technology for ammonia synthesis shows a reduction of around 80% in the ammonia production and storage lifecycle carbon footprint compared to the conventional route of coal-based hydrogen production and ammonia synthesis without CCUS technology. This reduction approaches the levels seen in routes based on wind power electrolysis for hydrogen production and subsequent green ammonia synthesis.

3.3 The carbon footprint of key green ammonia application cases

Transportation and power generation are the main application fields for ammonia energy, with heavy-duty ammonia trucks, ammonia-powered vessels, and ammonia co-firing in power generation being important research cases. For typical heavy-duty trucks, the ammonia consumption is 52.60 kg per hundred kilometers, while the corresponding diesel trucks consume 30 liters of fuel per hundred kilometers [26] . As for vessels, they consume 800 kg of ammonia per nautical mile, compared to 776 kg of fuel oil for conventional vessels per nautical mile [32,33] . Calculations show that under the green ammonia technology pathway, the carbon footprint of each application case is significantly lower than other technology pathways. Specifically, the green ammonia truck emits 24,117 gCO_2,eq per hundred kilometers, green ammonia vessels emit 374,568 gCO_2,eq per nautical mile, and green ammonia co-firing with coal emits 471 gCO_2,eq per kilowatt-hour. On the other hand, blue ammonia trucks emit 26,343 gCO_2,eq per hundred kilometers, and blue ammonia-powered vessels emit 665,088 gCO_2,eq per nautical mile. Green ammonia and blue ammonia demonstrate significant carbon emission advantages in the transportation sector compared to traditional fossil fuels, reducing carbon emissions by over 80% and 70%, respectively.

Referring to the research results of Li and Wang (2022)[34], a 600 MW coal-fired power generation unit has an average coal consumption of 300 gce/kWh, an overall power generation efficiency of 41%, and an annual operating hours of 4,000 h, resulting in an annual coal consumption of 720,000 tons. To achieve a 25% emission reduction goal (i.e., replacing 25% of coal fuel), approximately 280,000 tons of ammonia need to be blended. Calculations show that the full lifecycle carbon emissions of 1 kWh of coal-ammonia (grey ammonia) co-firing power generation is 887 gCO_2,eq/kWh, while 1 kWh of coal-fired power generation emits 570 gCO_2,eq/kWh. The full lifecycle carbon emissions of 1 kWh of coal-ammonia (green ammonia) co-firing power generation is 471 gCO_2,eq/kWh, resulting in a 17.36% reduction compared to coal-fired power generation. The results indicate that green ammonia also demonstrates carbon reduction advantages in the power generation sector, with the lowest carbon emissions in green ammonia power generation, while the lifecycle carbon emissions of power generation under gasification and natural gas reforming for ammonia production are higher than coal-fired power generation.

4 Results of the carbon footprint analysis

Currently, there is a significant difference in the carbon footprint of ammonia energy across various production, storage, and transportation technology pathways in China.

（1）There are notable differences in carbon footprints among different pathways. The route with the highest ammonia energy lifecycle carbon footprint in all scenarios is the route involving grid electricity electrolysis, Haber-Bosch (HB) synthesized ammonia, and liquid ammonia tanker transportation. On the other hand, the route with the lowest ammonia energy lifecycle carbon footprint is the one involving wind power electrolysis, HB-synthesized ammonia, and pipeline transportation of gaseous ammonia. Traditional fossil fuel-based ammonia production via HB synthesis and grid electricity electrolysis followed by HB-synthesized ammonia exhibit significantly higher carbon footprints compared to the wind power electrolysis route. The fuel production stage of the traditional fossil fuel-based route has the highest carbon emissions throughout the lifecycle. In summary, traditional fossil fuel-based routes such as fossil fuel-HB-synthesized ammonia and grid electricity electrolysis-HB-synthesized ammonia still have the highest carbon footprint in the entire ammonia energy production chain.

（2）Except for the wind power electrolysis-HB-synthesized ammonia route, the fuel production stage is the highest carbon-emitting stage in all other technology pathways. The use of green electricity in the hydrogen production, ammonia synthesis, and ammonia decomposition stages, such as the electric-hydrogen-ammonia, electric-hydrogen-ammonia-electric, electric-hydrogen-ammonia-hydrogen, or electric-hydrogen-ammonia-hydrogen-electric conversion routes, results in the lowest carbon footprint throughout the entire lifecycle. In the ammonia transportation stage, different transportation modes and distances significantly impact the carbon footprint of ammonia. Pipeline transportation and marine vessels show relatively lower carbon emissions, with low-carbon transportation advantages within distances of 1500 kilometers and beyond 2500 kilometers.

（3）Scenario-specific Analysis: Taking the scenario of using ammonia for hydrogen refueling stations as an example, the lowest carbon footprint is associated with the wind power electrolysis-HB-synthesized ammonia-pipeline transportation of gaseous ammonia-renewable electricity decomposition route, which is less than 20 gCO_2,eq/MJ. In comparison, scenarios involving ammonia for chemical plants and hydrogen/ammonia for power plants have shorter transportation distances and lower energy consumption for storage and transportation, resulting in lower ammonia energy lifecycle carbon footprints than the scenario of using ammonia for hydrogen refueling stations.

（4）Generally, the green ammonia route, such as the wind power electrolysis-HB-synthesized ammonia route, exhibits the lowest carbon footprint throughout the lifecycle. Green ammonia shows a significant carbon emission advantage over traditional fossil fuels in the transportation sector, reducing carbon emissions by over 80% for equivalent transportation services. In the power generation sector, green ammonia also demonstrates carbon reduction advantages.

（5）Compared to the traditional coal gasification-HB-synthesized ammonia route, the coal gasification combined

with carbon capture and storage (CCS) and HB-synthesized ammonia route (blue ammonia) shows a remarkable carbon reduction advantage. Blue ammonia, when used in the transportation sector, also presents a significant carbon emission advantage, reducing carbon emissions by over 70%.

Based on these findings, it is recommended to accelerate the research and development as well as the widespread adoption of green ammonia production technologies in China. This includes promoting large-scale and long-distance pipeline and marine transportation demonstrations. Additionally, active efforts should be made to advance blue ammonia-related technologies and demonstrations, providing potential technological options for the low-carbon development transition of the ammonia industry. Specific policy suggestions include:

（1）Deepen strategic research, based on the actual needs and technical characteristics of different application scenarios, explore the means of utilizing multiple ammonia energy.

（2）Accelerate the systematic deployment of the entire ammonia energy industry chain, expand ammonia energy storage and transportation infrastructure, and build a mature and stable ammonia energy supply system.

（3）Pilot projects such as photovoltaic hydrogen production and wind power hydrogen production will be carried out in some regions to build a diversified hydrogen energy supply pattern, promote the integrated development of hydrogen and ammonia, provide demonstration application projects for ammonia energy, and ultimately form a full industrial chain for large-scale application of ammonia energy.

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Chapter 2: Chinese ammonia full-chain levelized cost analysis for different application scenarios

1 Introduction to Ammonia Production Technologies

Similar to hydrogen production technologies, the production technology of ammonia (NH_3) significantly influences the cost of ammonia production, and there are substantial differences in the levelized cost among different ammonia production technologies. In China, the production of synthetic ammonia has a long history, and the technology is mature. Currently, the main method for ammonia production in China is the traditional fossil energy-based Haber-Bosch (HB) synthesis process. This process involves hydrogen production through coal gasification or natural gas reforming, nitrogen production through air separation, and the synthesis of ammonia using the HB process. Examples of such processes include coal gasification-HB synthesis ammonia and natural gas-HB synthesis ammonia.

On the other hand, alternative renewable energy-based ammonia production processes, such as electrolysis of water for hydrogen production followed by HB synthesis, or electrolysis of water for hydrogen production followed by electrochemical synthesis of ammonia, are still in the experimental and laboratory research phase and have not been widely implemented for large-scale production. In this study, considering the current status of ammonia production technology and industry development in China, various traditional fossil energy-based and new renewable energy-based ammonia production technologies were selected for analysis. These include coal gasification-HB synthesis ammonia, natural gas-HB synthesis ammonia, renewable energy electrolysis of water for hydrogen production followed by HB synthesis ammonia, and renewable energy electrolysis of water for hydrogen production followed by electrochemical synthesis of ammonia.

To analyze the levelized cost of each ammonia production technology, various parameters such as upfront investment, service life, operational and maintenance costs, energy consumption, etc., were determined for each technology. Data collection was conducted based on domestic and international literature research, and information from relevant production companies was gathered. A comprehensive assessment was made considering the current situation of ammonia production in China.

(a) Coal Gasification + HB Synthesis Ammonia: This technology is currently the mainstream ammonia production process in China. It involves obtaining hydrogen through coal gasification technology, nitrogen through air separation technology, and then synthesizing ammonia using the Haber-Bosch (HB) process with the addition of catalysts under high-temperature and high-pressure conditions. This technology is relatively mature and widely applied, with large-scale coal gasification-HB synthesis ammonia plants in China having an annual production capacity of up to 300,000 tons. However, this ammonia production process consumes a significant amount of fossil fuels, leading to the generation of substantial pollutants. Despite these environmental challenges, it remains a cost-effective method for ammonia synthesis. As China gradually advances in its transition to green and low-carbon energy, the coal gasification-based ammonia synthesis process may encounter various issues.

(b) Natural Gas Reforming + HB Synthesis Ammonia: This technology is similar to the coal gasification-based ammonia synthesis process, with the main difference being the use of natural gas reforming technology to produce hydrogen. Subsequently, the obtained hydrogen is combined with nitrogen from air separation, and the synthesis of ammonia is carried out using the Haber-Bosch (HB) process under high-temperature and high-pressure conditions. The key distinction lies in the utilization of natural gas reforming for hydrogen production instead of coal gasification. However, due to the higher cost of natural gas as a raw material for ammonia production compared to coal, this technology has a relatively higher comprehensive cost for ammonia synthesis. Currently, it is less commonly used in China's industrial ammonia production system compared to the coal gasification-based ammonia synthesis process.

(c) Electrolysis + HB Synthesis Ammonia: This technology is a relatively new and environmentally friendly ammonia production process. In this process, ammonia synthesis involves electrolyzing water to obtain hydrogen and using air separation to obtain nitrogen. The hydrogen and nitrogen are then input in a 1:3 ratio and subjected to the Haber-Bosch process with Fe, Ru, Co-Mo catalysts at temperatures ranging from 400 to 500°C. In the process of ammonia production using renewable energy + HB synthesis ammonia technology, all the power comes from renewable energy sources, ensuring no carbon dioxide emissions during ammonia production. The study selects grid electricity, nuclear power, wind power, solar power, and hydropower as the power sources for the entire process of electrolysis + HB synthesis ammonia, and calculates the leveling cost of ammonia production under different power sources.

(d) Electrolysis + Electrochemical Synthesis Ammonia: Electrochemical synthesis of ammonia differs from traditional fossil fuel-based ammonia production and thermochemical synthesis in that it does not involve the Haber-Bosch process for ammonia synthesis. Instead, it directly synthesizes ammonia from air and water, with the primary cost of ammonia production being associated with electricity consumption. Currently, mainstream electrochemical synthesis of ammonia can be categorized into three types: solid electrolyte, molten salt electrolyte, and liquid electrolyte. Although electrochemical synthesis of ammonia technology offers significant advantages in terms of being green and low carbon, it is still in the experimental research and development phase. The technology has high requirements for ammonia production, and there are challenges such as unstable ammonia production efficiency and low reaction rates, placing it in the early stages of development. The study is based on the current development status of electrochemical ammonia synthesis technology in China, referencing both domestic and international research results, and selects PEM electrolysis + electrochemical synthesis ammonia for analysis.

2 Key Data on Ammonia Energy Production in China

Based on the actual situation of ammonia energy production in China as of the end of 2021, various key parameters

for ammonia energy production technologies were compiled through extensive literature research both domestically and internationally. Public parameters were adjusted by referencing relevant statistical yearbooks, researching average market trading prices nationwide, and considering the actual situation of hydrogen energy production in China.

The calculation and parameter setting for the normalized cost of the ammonia production process differ slightly from those of hydrogen energy. Since the predominant ammonia production technology in China currently involves coal gasification and the Haber-Bosch synthesis process (Coal Gasification + HB), and applications of the electrically generated hydrogen + HB synthesis ammonia process and other new green ammonia production technologies are limited and primarily in the experimental development stage, data availability is relatively scarce. In the ammonia production process, ammonia synthesis plants are assessed as a whole for investment cost-related indicators. Therefore, the study calculates and analyzes the normalized cost for traditional fossil energy-based ammonia production technologies using the entire project as a unit. The calculation methods for electrically generated hydrogen + HB synthesis ammonia and electrolysis + thermochemical synthesis ammonia are essentially the same as the normalized cost calculation method for electrolysis.

Table 1 summarizes the basic parameters of the current traditional fossil energy-based ammonia production technologies in China, namely, coal gasification + Haber-Bosch (HB) synthesis ammonia and natural gas reforming + HB synthesis ammonia. The main parameters include equipment acquisition, civil engineering, installation engineering, and necessary operating costs, as well as energy consumption expenses.

The data for the Coal Gasification + HB Synthesis Ammonia project are sourced from a large-scale synthesis ammonia project with an annual production capacity of 300,000 tons and a total investment of 1.5 billion yuan in Hubei Province, China, in 2022. The coal gasification technology selected is the AFB advanced fluidized bed process.

The data for the Natural Gas Reforming + HB Synthesis Ammonia project is referenced from the basic elements of the Coal Gasification + HB Synthesis Ammonia project. The electric turbine-driven process route is selected, and the ammonia production energy consumption data are based on research findings by Wang Xiang (2019)[1] and Ren et al. (2022)[2]. Some key parameters are adjusted based on the actual ammonia production situation in China.

Table.1 Basic parameters of coal gasification+HB synthetic ammonia and natural gas reforming+HB synthetic ammonia projects

Projects	Unit	Technology Roadmap	
		Coal Gasification +HB	Natural Gas +HB
Equipment purchase cost	Ten thousand yuan	61454.95	61454.95
Civil engineering cost	Ten thousand yuan	26890.52	26890.52
Installation engineering cost	Ten thousand yuan	36149.82	36149.82
Equipment service life	year	10	10
Land use period	year	20	20
Reserve funds	Ten thousand yuan	25504.71	25504.71
Number of employees	human	800	800
Employee salaries	Yuan/year	50000	50000

Annual output	Ten thousand tons	30	30
Coal/natural gas consumption	$Kg/kgNH_3$	1.14	0.76
Electricity consumption	$Kwh/kgNH_3$	1.196	0.75
Coal/Natural Gas Price	Yuan/kg	1	4.2
Electricity price	Yuan/kwh	0.6	0.6
Number of device sets	set	120	120
Annual operating days	day	350	350
Land occupation area	m^2	30000	30000

Due to the ability to obtain ammonia through electrolysis for hydrogen (HB synthesis of ammonia), based on the technical route parameters for electrolysis for hydrogen, and referring to the equipment investment parameters for coal gasification synthesis of ammonia, the investment cost of HB synthesis of ammonia equipment is set at 100 million RMB. Other parameters are the same as those for coal gasification synthesis of ammonia.

Table 2 summarizes the key parameters of China's electrolysis for hydrogen technical route. This includes various power generation technologies such as grid electricity, nuclear power, wind power, solar power, hydropower, and basic parameters of AE and PEM electrolysis cells. Other parameters can be referred to the key parameters of the electrolysis for hydrogen production process in the previous section. The investment cost and operating time of various power generation technologies are referenced from the 2021 national power industry statistics of the National Energy Administration [3], "China Power Development Analysis Report 2021" [4], and the investment cost and lifespan of AE and PEM electrolysis cells are referenced from the research results of Li Jianlin et al. (2021) [5]. These values are then reasonably assessed based on the current application market cost prices of power generation technologies and electrolysis for hydrogen technologies in China.

Since the electrolysis for hydrogen + HB synthesis of ammonia process is rarely applied in large-scale ammonia production projects in China, and obtaining relevant project data is challenging, and the equipment investment and operating costs of the HB synthesis of ammonia process are relatively high in the entire ammonia production system. For the cost of the HB synthesis of ammonia system in the electrolysis for hydrogen + HB synthesis of ammonia process, 70% of the overall investment in the coal gasification + HB synthesis of ammonia process is considered as part of the capital cost in the electrolysis for hydrogen + HB synthesis of ammonia process. Other parameters are reasonably assessed based on the current actual situation of ammonia production processes in China.

Table.2 Basic parameters of China's electrolytic water hydrogen production technology

	Unit Investment	The proportion of operating and maintenance cost	Annual operating time	Service life	Operating efficiency	working temperature
Unit	10000yuan /kw	%	hours	year	%	℃
Grid power	-	-	5000	10	95	-
nuclear power	17500	8	7800	40	40	-
Wind power	7500	5	2100	25	95	-

Photovoltaic power	4500	6	1300	25	95	-
hydropower	11000	2.3	3800	50	100	-
AE	5000	2.5	-	10	60-75	70-90
PEM	10000	2.5	-	30	70-90	70-80

For the electrochemical synthesis of ammonia technical route, currently, domestic electrochemical synthesis of ammonia in China is still in the laboratory research and development stage and has not been applied to large-scale industrial synthesis of ammonia production. The study refers to the research results of Bicer and Dincer (2017) [5], and Gomez et al. (2019) [6] on PEM electrochemical synthesis of ammonia. The capital cost of PEM electrochemical synthesis of ammonia is approximately 80% of the capital cost of PEM electrolysis for hydrogen + HB synthesis of ammonia. The investment in power generation is the same as that for electrolysis for hydrogen + HB synthesis of ammonia, while other costs are referenced from the coal gasification + HB synthesis of ammonia and electrolysis for hydrogen + HB synthesis of ammonia projects, combined with the actual situation of ammonia production in China for reasonable assessment.

Table 3 presents the public parameters of ammonia production in China. Various fuel prices are based on the latest average market prices in China and remain consistent with the public parameters of hydrogen production in the previous section.

Table.3 Public parameters for ammonia production in China

	Unit	Figure
Discount rate	%	8
Coal price	t	1000
Natural gas price	t	4200
Electricity price	Yuan	0.6

3 Calculation results of levelized cost for ammonia production process

In general, the normalized cost of ammonia production in the analyzed stages of China's ammonia energy production consists of three parts: capital cost, operation and maintenance cost, and energy consumption cost. Capital cost includes investment costs in various production technology equipment and power generation projects. Operation and maintenance cost covers the necessary expenses incurred during the daily operation and maintenance of various ammonia energy production technologies, such as labor costs, maintenance fees, and repair costs. Energy consumption cost includes the cost of raw materials and energy consumption, such as electricity, required by various ammonia production technologies.

We can illustrate the normalized cost results for different ammonia energy production technologies, showing significant differences among various ammonia production technologies. Overall, the normalized cost of ammonia energy production for different technology routes ranges from 2.69 to 10.95 yuan/kg. Among them, the coal gasification + HB synthesis of ammonia technology has the lowest production cost at 2.69 yuan/kg, while the highest

production cost is for photovoltaic PEM + HB synthesis of ammonia at 10.95 yuan/kg. The production cost of ammonia for natural gas reforming + HB synthesis is 4.46 yuan/kg. The production cost of electrolysis + HB synthesis of ammonia ranges from 5.17 to 12.97 yuan/kg, while for PEM electrochemical synthesis of ammonia, it ranges from 4.80 to 11.32 yuan/kg. Among the electrolysis + HB synthesis of ammonia and PEM electrochemical synthesis of ammonia technologies, those utilizing nuclear power as the source of electricity have the lowest production costs, mainly due to their longer operating hours and higher ammonia production.

The cost structure of different ammonia production technology routes is primarily composed of energy consumption costs. However, for electrolysis + HB and PEM electrochemical synthesis of ammonia technologies, the high investment costs in various renewable energy generation technologies and electrolysis cells lead to higher capital costs in their overall normalized costs. Among them, photovoltaic electrolysis + HB synthesis of ammonia and electrochemical synthesis of ammonia technologies have higher overall production costs due to their shorter operating hours, higher investment costs, and lower ammonia production. Therefore, the key factor affecting renewable energy-based ammonia production is the capital cost, specifically the investment cost of power generation equipment.

In the study, the energy consumption cost mainly considers electricity, coal, natural gas, and other energy consumption costs. In traditional fossil fuel-based ammonia production technologies such as coal gasification + HB synthesis of ammonia and natural gas reforming + HB synthesis of ammonia, the energy consumption cost primarily consists of ammonia production electricity consumption and coal or natural gas consumption. In renewable energy-based ammonia production processes, the energy consumption cost mainly comprises electricity generation costs.

4 Introduction to Ammonia Energy Storage, Transportation, and Application Stages

Ammonia energy can be transported in gaseous or liquid form through different storage and transportation methods to designated application scenarios. Gaseous ammonia can be transported through ammonia gas tanker trucks and ammonia pipelines, while liquid ammonia can be transported using liquid ammonia tanker trucks, liquid ammonia box trucks, and ocean vessels (Table4).

(a) Gas/Liquid Ammonia Tanker Trucks:

Tanker trucks are the primary means of storage and transportation for both gaseous and liquid ammonia in China. Due to the historical transportation of ammonia in liquid form to applications such as chemical plants, liquid ammonia tanker trucks are the most widely used transportation technology. However, considering that ammonia can also be transported in gas form, gas ammonia tanker trucks are used in this form of transportation. Due to the flammable and hazardous nature of ammonia, road transport in tanker trucks is limited to a maximum of 10 tons per trip according to China's "Standards for the Transport of Dangerous Goods Vehicles." These trucks typically have a double-layer metal framework and are constructed with cold-rolled steel plate and aluminum alloy. They can carry a maximum of 10 tons of liquid ammonia in one trip, and the entire vehicle costs around 300,000 yuan, suitable for short-distance transportation within 200 km.

(b) Liquid Ammonia Tanker Trucks:

Similar to liquid hydrogen tanker trucks, liquid ammonia tanker trucks consist of a powerhead, entire vehicle tow tray, and liquid ammonia storage tank. After the production of ammonia, it is cooled to -33°C to liquefy it and then loaded into the liquid ammonia storage tank. Liquid ammonia tanker trucks can transport nearly 30,000 kg of liquid ammonia in a single trip, significantly improving transportation efficiency compared to liquid ammonia box trucks. However, due to the high overall cost of liquid ammonia tanker trucks, with one truck costing between 500,000 to 700,000 yuan, they are not widely used in China at present.

(c) Pipeline Transport:

The principles of pipeline transport are similar to those of hydrogen gas pipeline transport. It requires compressing gaseous ammonia to a certain pressure level. The investment cost per kilometer of pipeline transport is relatively high, and the construction technology presents significant challenges. It is suitable for large-scale, long-distance transportation. However, gas ammonia pipeline transport technology has not been applied in China yet. Currently, only some hydrogen pipeline projects have been put into operation. China still lags behind Japan and South Korea in the fields of hydrogen and ammonia pipeline transport.

(d) Ocean Vessels:

Similar to the technology used for transporting liquid hydrogen by sea. There are currently no domestic applications of ocean vessels for the storage and transportation of liquid ammonia in China. However, countries such as Japan, South Korea, and Australia have conducted experiments related to marine transport and achieved certain results. The major advantage of marine vessel transport is the large-scale storage and transport of liquid ammonia in a single trip, suitable for long-distance inter-regional and international transport.

Regarding the application scenarios of ammonia energy, it can be directly used in transportation, chemical industry, power generation, etc. In China, ammonia energy is mainly used in the chemical industry and has not yet been applied in transportation and power generation. In the transportation sector, ammonia fuel supply stations are used, while in the power generation sector, there are mainly ammonia power plants. Ammonia energy can also be decomposed into hydrogen energy, indirectly used in transportation, chemical industry, power generation, and space launch fields. In this case, hydrogen refueling stations are used in the transportation sector, and hydrogen power plants are used in the power generation sector.

Therefore, based on the current practical situation of ammonia energy storage, transportation, and application in China, the study has defined five transportation technology routes: gas ammonia tanker trucks, liquid ammonia tanker trucks, liquid ammonia box trucks, pipeline transport, and ocean vessels. Application scenarios include hydrogen refueling stations, ammonia fuel supply stations, hydrogen steel plants, chemical plants, hydrogen power plants, ammonia power plants, and space launch centers. The transportation distances of ammonia energy to various application scenarios are set to be consistent with hydrogen energy.

Table.4 Technical route for hydrogen energy industry chain storage and transportation application link

Storage And Transportation Technology	**Application Scenarios**
Gas ammonia - gas ammonia compartment car	chemical plant
Gas ammonia - pipeline transportation	Hydrogen refueling station
Liquid ammonia - liquid ammonia tank truck	Ammonia fuel supply station

Liquid ammonia - liquid ammonia compartment car	Hydrogen power plants
Liquid ammonia - marine vessels	Ammonia power plant
	Hydrogen energy steelmaking plant
	Space Launch Center

5 Key parameters for ammonia energy storage, transportation, and application processes

For the transportation and application stages of ammonia energy, Table 5 summarizes the investment costs, energy consumption, and operating time parameters for transporting hydrogen using gas ammonia tanker trucks, liquid ammonia tanker trucks, and liquid ammonia tankers. The data for long gas ammonia tanker trucks, liquid ammonia tanker trucks, and liquid ammonia tankers are collected based on the current transportation of ammonia energy in China, with some data obtained through research from a box truck manufacturing company in Hubei Province, China.

Since there are no completed application projects for ammonia pipeline transportation in China, the data for pipeline transport are based on the data from the Ji Yuan to Luo Yang 25 km hydrogen pipeline project in China, consistent with hydrogen transportation. Relevant energy consumption data are converted based on the energy density of ammonia energy, as shown in Table 6. The transportation of hydrogen by liquid ammonia ships has not been widely promoted in China. The main parameters for marine vessels are based on research data from Niermann et al. (2019) [8]and Kim et al. (2021)[9], with some parameters being reasonably evaluated based on the actual situation in China, as shown in Table 7.

Table.5 Main parameters for transporting ammonia by gas ammonia tank trucks, liquid ammonia tank trucks, and liquid ammonia tank trucks

	Ammonia Transport Capacity	Price	Salary	Toll	Maintenance fee	Premium	Fuel consumption	Speed	Age limit
Unit	kg/once	10000 yuan	10000 yuan/year	yuan /km	yuan/km	10000 yuan/year	L/ 100 kilometers	km/h	year
Gas ammonia compartment car	9000	30	40	0.6	0.3	1	25	50	10
Liquid ammonia car	10000	30	40	0.6	0.3	1	25	50	10
Liquid ammonia	27000	60	40	0.6	0.3	4	25	50	10

tank truck						

Table.6 Main parameters of pipeline transportation

	Ammonia conveying capacity	Construction cost	Salary	Distance	Compression energy consumption	Age limit
Unit	10000t/year	10000yuan	10000 yuan/ year	km	kWh/kg	year
Pipeline transportation	21.97	584	40	25	0.18	20

Table.7 Main parameters of liquid ammonia ship hydrogen transportation

	Ammonia conveying capacity	Shipping price	Salary	Fuel Consumption	Speed	Age limit	Operation and maintenance costs
Unit	t/once	10000yuan	10000 yuan /year	t/day	km/h	year	万元/天
Liquid ammonia vessel	330000	24500	800	56	27.78	15	3.5

For different application scenarios, considering that ammonia energy can be directly applied in various fields such as transportation, industry, chemistry, and power, as well as through ammonia cracking to produce hydrogen for hydrogen applications, data related to ammonia cracking for hydrogen production is referenced from the study by Yi et al. (2020) [10]. Based on the actual situation of ammonia energy application in China and the comprehensive potential and prospects for multi-field application of ammonia energy in the future, the study sets the distance from the ammonia production plant to different application sites.

Assuming a distance of 130 km from the ammonia production plant to the hydrogen refueling station and ammonia fuel supply station, the study considers typical demonstration projects in China such as hydrogen steel plants, chemical plants, hydrogen power plants, and ammonia power plants. These projects mainly use self-produced ammonia, meaning there are subsidiary ammonia production facilities within or near the plant area. The transportation distance is set based on the actual average land area of steel plants, chemical plants, hydrogen power

stations, and other scenarios in China, combined with the radius of industrial gas transportation in China.

As ammonia energy can be directly used in ammonia fuel supply stations and ammonia power plants, and ammonia can also be applied to hydrogen refueling stations, chemical plants, hydrogen power plants, and space launch centers through cracking for hydrogen production, the transportation distances for various application scenarios are consistent with those for hydrogen energy. The basic parameters for different application scenarios set by the study are shown in Table 8, and the common parameters used in the study are derived from the average market level in China in 2021, with specific values listed in Table 9.

Regarding the use of ammonia energy in the field of power generation, Wang (2019)[11]indicated that a 200 kW ammonia combustion generator consumes 3000 kg of ammonia per day, with an electricity generation efficiency of 29%. Therefore, 1 kWh of electricity consumes 0.67 kg of ammonia.

Ammonia co-firing technology refers to the co-combustion of ammonia with coal in boilers, achieving stable combustion and low carbon emissions. In the field of ammonia co-firing power generation, significant breakthroughs have been made. The ammonia co-firing ratio has reached 35%, far ahead of Western countries. In 2022, Japan's JERA Mikuni Thermal Power Plant achieved a demonstration project of 20% ammonia co-firing, achieving certain results.

For the application of ammonia fuel in the internal combustion engine field, in December 2022, the country's first heavy-duty truck project sample vehicle with ammonia and natural gas hybrid power successfully rolled off the production line at the Gangji Industrial Community in Changfeng County, Anhui Province, China. For a fully loaded condition of an 18-ton heavy-duty truck, the fuel cost per kilometer using diesel is approximately 4.6 yuan, using natural gas is about 4.2 yuan, and using a full ammonia internal combustion engine, the cost is only 3.6 yuan per kilometer. Currently, the heavy-duty truck sample vehicle with ammonia and natural gas hybrid power runs with a 30% ammonia blend, reducing carbon emissions by 30%.

Table.8 Different application scenario settings

Application scenarios	Usage	Unit	Distance
Hydrogen refueling station	Hydrogen production through cracking	km	130
Ammonia fuel supply station	Direct use	km	130
Steel plant	Hydrogen production through cracking	km	10
chemical plant	Direct use	km	5
Ammonia power plant	Direct use	km	2
Hydrogen power plant	Hydrogen production through cracking	km	2
Space Launch Center	Hydrogen production through cracking	km	10

Table.9 Common Parameters

Parameter	Unit	Figure

Discount rate	%	8
Coal price	yuan/t	1000
Natural gas price	yuan/t	4200
Electricity price	yuan/kWh	0.6
Oil price	yuan/L	7
Gasification power consumption	kWh/kgNH_3	0.18
Liquefaction electricity consumption	kWh/kgNH_3	0.6
Electricity consumption for ammonia cracking hydrogen production	kWh/kgNH_3	0.4
Gross profit margin of ammonia transportation	%	15

6 Calculation Results of Levelized Costs for Ammonia Energy Storage, Transportation, and Application

We can show the standardized cost structure of storage, transportation, and application processes for different storage and transportation technologies and application scenarios of China's ammonia energy. The storage and transportation application costs of ammonia energy vary significantly under various storage and transportation technologies and application scenarios, with an overall cost ranging from 0.14 to 1.65 yuan/kg. Among them, the scenario where the gas ammonia pipeline is transported to the ammonia power plant has the lowest levelized cost of 0.14 yuan/kg for ammonia energy storage and transportation, and the scenario where the liquid ammonia tank is transported to the space launch center has the highest levelized cost of 1.65 yuan/kg for ammonia energy storage and transportation. In other representative scenarios, the leveling cost of each storage and transportation route in the hydrogen refueling station scenario is 0.51-1.06 yuan/kg, with the pipeline transportation and storage route being the lowest and the liquid ammonia tank vehicle storage and transportation route being the highest; The leveling cost of each storage and transportation application route in the ammonia fuel supply station scenario is 0.26-0.60 yuan/kg; The unit ammonia energy cost for storage and transportation applications in scenarios such as steel mills, hydrogen power plants, and ammonia power plants is all below 1 yuan.

Among them, pipeline transportation is the lowest cost ammonia energy storage and transportation method in various application scenarios. Gas hydrogen pipeline transportation ammonia energy power station is the lowest cost route among all routes, with a cost of 0.48 yuan per kilogram of ammonia energy storage and transportation application link. In the application scenarios of hydrogen refueling stations, the lowest cost is the gas ammonia pipeline transportation route, followed by the gas hydrogen long pipe trailer route, and the highest cost is the liquid ammonia tank truck route.

In various application scenarios, since ammonia fuel supply stations and ammonia power plants can directly use ammonia energy for production, there is no need to decompose ammonia energy into hydrogen energy again, so there is no leveling cost in the application process. In addition, the transportation distance of the above two scenarios is relatively short, so the overall leveling cost of this scenario is lower compared to other scenarios.

7 Levelized cost results for the entire ammonia energy industry chain

We can show the cost leveling results of China's ammonia energy industry chain for different application scenarios. Due to the many routes of electrolysis water for hydrogen production+HB synthesis of ammonia and electrochemical synthesis of ammonia, only the application results of AE electrolysis water for hydrogen production+HB synthesis of ammonia for storage and transportation are listed.

It is showed the levelized cost results of the entire ammonia energy industry chain in the application scenario of hydrogen refueling stations. The cost of leveling the entire hydrogen energy industry chain in this application scenario ranges from 3.19 to 14.03 yuan/kg. Among them, the leveling cost of coal hydrogen production gas ammonia pipeline transportation route is the lowest, 3.19 yuan/kg, and the leveling cost of photovoltaic PEM water electrolysis hydrogen production liquid ammonia liquid ammonia car route is the highest, 14.03 yuan/kg. In the entire industry chain cost of various production, storage, and transportation technology routes, the levelized cost of the natural gas reforming hydrogen production+HB synthesis ammonia route is 4.36-4.91 yuan/kg. In the other electrolysis water hydrogen production+HB synthesis ammonia routes, the levelized cost of nuclear power and hydropower electrolysis water routes is relatively low, mainly due to their high annual operating time and ammonia production. From the perspective of the leveling cost of different links in the entire ammonia energy industry chain, all technical routes have the highest leveling cost in the ammonia production process and the lowest leveling cost in the application process.

It is showed the levelized cost results of China's entire ammonia energy industry chain in the scenario of ammonia fuel supply stations. Due to the fact that ammonia can be directly used as a fuel for transportation, in this scenario, there is no application link for leveling costs. The leveling costs of all routes range from 2.95 to 12.17 yuan/kg, and the distribution of leveling costs is basically consistent with the hydrogen refueling station scenario. The cost of ammonia production still accounts for the highest proportion of the entire industry chain cost.

It is showed that the levelized cost results of China's ammonia energy industry chain in the application scenario of chemical plants. Due to the fact that ammonia can be directly used as a chemical raw material in the chemical industry, there is no application link to level the cost in this scenario. The leveling cost of all routes is between 2.84-12.07 yuan, and the cost of ammonia production still accounts for the highest proportion of the entire industry chain cost. Due to the small difference in storage and transportation distance between steel mills and power plants and chemical plants, the cost of leveling the entire industry chain is similar to that of chemical plants.

8 Results of the cost analysis

(1). There is a significant difference in the leveling cost under different hydrogen and ammonia energy storage and utilization technology routes. In the hydrogen and ammonia production end, the main manifestation is that the leveling cost of traditional fossil energy hydrogen and ammonia production is significantly lower than that of renewable energy electrolysis water hydrogen production and renewable energy electrolysis water hydrogen production - HB synthetic ammonia. At the hydrogen energy storage and transportation end, pipeline transportation is the lowest cost leveling storage and transportation technology, and liquid hydrogen tank trucks are the highest cost storage and transportation technology. The cost of hydrogen liquefaction accounts for the largest proportion of the cost of liquid hydrogen storage and transportation. At the ammonia energy storage and transportation end, pipeline transportation remains the lowest leveling cost storage and transportation technology, and liquid ammonia tank trucks are the highest leveling storage and transportation technology. On the application side of hydrogen

energy, the main application costs of hydrogen energy in hydrogen refueling stations are the cost of leveling the construction of hydrogen refueling stations and the consumption of hydrogen refueling electricity. Other scenarios do not have the cost of leveling the application links.

(2). Overall, the standardized cost of ammonia production for various ammonia production technology routes ranges from 2.69 to 10.95 yuan/kg. Among them, the ammonia production cost of coal gasification+HB synthetic ammonia process is the lowest, 2.69 yuan/kg, the ammonia production cost of photoelectric PEM+HB synthetic ammonia is the highest, 10.95 yuan/kg, and the ammonia production cost of natural gas reforming+HB synthetic ammonia is 4.46 yuan/kg. The cost of ammonia production through electrolysis of water and HB synthesis ranges from 5.17 to 12.97 yuan/kg, while the cost of PEM electrochemical ammonia production ranges from 4.80 to 11.32 yuan/kg.

(3). The storage and application costs of ammonia energy vary significantly in various storage and transportation technologies and application scenarios, with an overall cost ranging from 0.14 to 1.65 yuan/kg. Among them, the scenario where the gas ammonia pipeline is transported to the ammonia power plant has the lowest levelized cost of 0.14 yuan/kg for ammonia energy storage and transportation, and the scenario where the liquid ammonia tank is transported to the space launch center has the highest levelized cost of 1.65 yuan/kg for ammonia energy storage and transportation. In other representative scenarios, the leveling cost of each storage and transportation route in the hydrogen refueling station scenario is 0.51-1.06 yuan/kg, with the pipeline transportation and storage route being the lowest and the liquid ammonia tank vehicle storage and transportation route being the highest; The leveling cost of each storage and transportation application route in the ammonia fuel supply station scenario is 0.26-0.60 yuan/kg; The unit ammonia energy cost for storage and transportation applications in scenarios such as steel mills, hydrogen power plants, and ammonia power plants is all below 1 yuan.

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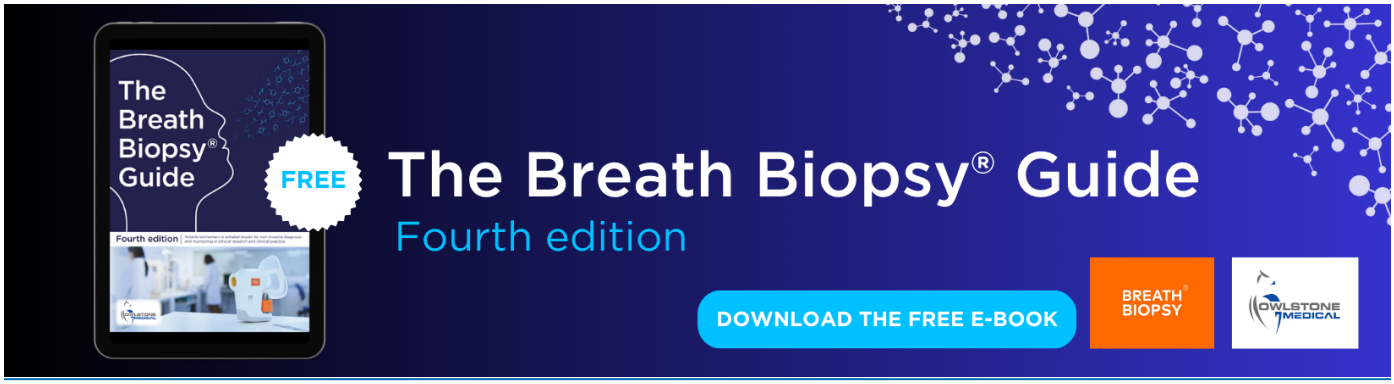

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The potential of digital convergence and sharing of consumer goods to improve living conditions and reduce emissions

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Abstract

Access to modern energy services (entertainment, food preparation, etc) provided by consumer goods remains unequal, while growing adoption due to rising incomes in Global South increases energy demand and greenhouse gas emissions. The current model through which these energy services is provided is unsustainable and needs to evolve—a goal that emerging social and technological innovations can help to achieve. Digital convergence and the sharing economy could make access to appliances more affordable and efficient. This article estimates the effect of innovations around digital convergence and sharing in a highly granular, bottom-up representation of appliances. We simulate changes in demand for materials and energy, assuming decent living standards for all and global warming limited to 1.5 °C. By 2050, these innovations could attenuate the increase in the number of appliances to 135% and reduce overall energy demand by 28%. The results contribute to understand under which conditions digital convergence and sharing can improve living standards and climate mitigation.

1. Introduction

The way in which the production and use of consumer goods[1] is organized is problematic, for several reasons. Emissions from appliance use are rising rapidly, threatening efforts towards climate mitigation. Appliances are among the fastest-growing categories of energy demand, given rising ownership of devices that is driven by increasing income [1]. Appliances already account for 15% of global final electricity demand, or one-third of the energy consumed in buildings (including lighting and cooking) [2]. If demand growth continues to outstrip efficiency gains, one in six units of final energy demand in 2050 will go to appliances, even in a low energy demand (LED) scenario [3]. On the one hand, income growth can have nonlinear effects on energy demand in developing countries [4]. On the other hand, global warming should further increase demand for services such as cooling [5]. Crises such as the pandemic could either attenuate or reinforce the increase in energy demand, depending on whether recovery leads to a more intensive utilization of appliances or the duplication of residential and non-residential space [6].

Access remains extremely unequal to basic appliances that provide modern energy services such as televisual entertainment, food and medicine refrigeration, or automatic laundry washing [7, 8]. For example, in Africa, average ownership rates per 100 households of TVs, fridges, and washing machines are just 17, 10, and 2, respectively—compared to 98, 95, and 92 in the Global North [9]. Attaining universal access to modern energy services by 2030 (UN SGD 7) will be challenging [10, 11]. Over 700 million people still lack access to reliable electricity, particularly in Central and Southern Asia as well as Sub-Saharan Africa (SSA) [12].

[1] Consumer goods are products that consumers buy to perform services (lighting, cooking, entertainment, etc) for their own use, as opposed to capital goods mainly used in business. We refer to consumer durable goods using energy in buildings (including appliances and electronics but not furniture or vehicles), excluding fixed thermal comfort systems that are often covered in a separated category. They include all sort of plug-loads in buildings that are not fixed (i.e. portable, not permanently installed in a location). Large and small household appliances, such as refrigerators and radio alarm clocks respectively, are a major group of consumer goods. In the rest of this paper, we refer to these goods interchangeably as 'consumer goods', 'appliances,' 'equipment,' or 'devices.'

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Current service provision is too costly, inefficient, and pollutive. Income is an important determinant for the acquisition of energy-using assets [4], and prices of appliances remain high for much of the population in low-income countries. Even though the prices of household appliances have declined over time—by 20% on average over the last 25 years in the European Union [13]—they remain out of reach for many in the Global South. In addition, there are variations within this region; for instance, an Indian household faces higher prices for TVs, fridges, and washing machines in terms of purchasing power parity than one in Brazil or South Africa [14]. Higher per capita income in the Global South by 2050—they are expected to double in the 'middle of the road' IPCC SSP2 scenario—would still not be enough to provide universal access [9].

Efficiency gains in consumer goods have slowed down in the past decade, and have stabilized for major appliances since 2014 [15]. On the other hand, smaller devices have increased in number twice as quickly as major appliances since 2010 [1]. Even though small consumer electronics (e.g. tablets or smartphones) have low energy consumption, they exhibit relatively higher manufacturing requirements (i.e. higher embodied energy) [16, 17].

In this context, an increasing number of voices calls for the importance of demand-side solutions in climate mitigation [18, 19], in a way that reduces disparities and improves the lives of the poor households [20].

We need to find a better way to modernize the provision of energy services with more accessible, efficient, and cleaner appliances. Previous research has focused on quantifying energy requirements from normatively defined services [e.g. 14, 21] and changes in access to services driven by rising incomes [9]. However, these analyses assume no technological change by 2050. There is no investigation of the contribution of new social and technological innovations that perform multiple services (e.g. TVs and radios replaced by smartphones) or serve multiple people (e.g. thermal equipment shared at the building level) that can improve access to modern services and lower energy demands.

New business models are emerging based on technological and social innovations, most often digitally enabled, that can change the way goods and services are provided [22]. In terms of transforming the production and use of consumer goods that provide important energy services, two particularly promising trends are digital convergence and the sharing economy.

Digital convergence refers to the tendency of standalone devices to converge into multifunctional equivalents that provide multiple services [23]. The typical example is the smartphone, which converged previously unrelated technologies such as the telephone, television, and computer [24]. Smartphones (and apps) can substitute at least 17 devices, from alarm clocks to GPSs and radios, with 30 times less power in use and 100 times less power in standby [3]. Even the basic mobile phone (feature phone) achieved an unprecedent speed of diffusion, becoming the most democratic technology in less than two decades [25]. These highly efficient devices have provided access not only to communication, but also to a wide range of services such as financial transactions in a developing context [26].

The *sharing economy* denotes multiple people using an otherwise underutilized good, such as cars, homes, or devices, as opposed to individual ownership. Digitalization has helped to up-scale the local sharing initiatives. In large scale, the sharing practice could significantly reduce the number of physical goods without loss of consumer welfare [27]. In the U.S., for example, 36% of the population reported the use of ridesharing services regularly in 2021, compared to 15% in 2015 [28]. In 2016, ridesharing apps displaced the sales of roughly two million cars worldwide, particularly in China (960 000) and India (540 000) [28]. Collective living or working makes people more likely to share more amenities, such as lighting, space heating/cooling, and appliances. Previous research shows evidence that collective living reduces emissions by an average of 0.3 tCO_2eq/cap per year [29]. Finally, several types of devices are increasingly being shared at building or community level. For example, shared laundry rooms are common in multifamily buildings in North America, and increasingly in other parts of the world too, with an estimated reduction in greenhouse gas (GHG) emissions of 26% [30]. Shared devices can run more efficiently at the lowest energy consumption and operational cost [29]. By reducing the number of devices through collective use, sharing also has the potential to reduce the embodied energy associated with avoidable goods [27]. Therefore, moving from owning to sharing presents several benefits such as more intensive use, minimizing waste (circular economy), and reducing material needs (dematerialization).

Both digital convergence and the sharing economy can help to significantly reduce the number of consumer goods required to meet the same needs. They open promising avenues to lower both the energy demand and the material consumption from appliances—provided that the impacts on direct energy/materials use and rebounds remain limited compared to the potential on enhancing efficiency and structural change [16, 31]. More importantly, digital convergence and sharing could make services cheaper, enabling widespread access to the modern services provided by consumer goods (entertainment, communication, etc), particularly for the more deprived population in developing countries.

This paper advances in the need to understand the effects of digitalization on climate mitigation [32, 33].

It does so by examining the effects of digitally enabled innovations such as digital convergence and sharing. The paper illustrates the potential of these innovations to improve standards of living and limit the raise in emissions in consumer goods—a category often overlooked in the analysis of energy and climate change. In particular, the impacts of digital convergence have only been estimated in Grubler *et al* [3], but at more aggregated level and not clearly autonomized.

The rest of the paper evolves as follows. Section 2 presents the empirical approach of this study. Section 3 shows the results and the societal benefits. Section 4 concludes with the main implications of the results, limitations and remaining questions for future research.

2. Methods

To estimate the impact of digital convergence and the sharing economy on providing decent living standards (DLSs) in the Global South and reducing energy and materials needs, we employ a mixed-methods approach. Here we describe more in detail the procedures, techniques and validations followed in this research.

2.1. Data sources and collection

We consider a wide range of consumer goods across different categories and domains of application. To estimate the stock of appliances and energy demand in 2020, we depart from existing projections in the Global Energy Assessment (GEA) [34] and the LED study [3], an influential and highly detailed scenario for decarbonization, including an explicit representation of consumer goods. We have enlarged the sample of goods and validated the estimates based on micro-level data from national representative statistics and household surveys [e.g. 35, 36], meta-analysis [e.g. 9], available datasets from international organizations [e.g. 37, 38] and peer-reviewed studies [e.g. 39].

To achieve a finer-grained categorization of consumer goods, we distinguish demand from residential and non-residential (commercial and services) sectors. In addition, we consider a broader range of consumer goods, comprised in several categories: hygiene (e.g. hot water, washing machine); food preparation (e.g. refrigerator, electric stove); communication & entertainment (e.g. mobile phone, television, personal computer); lighting (all types of lamps), thermal demand (e.g. fan, portable air conditioner), and miscellaneous (mainly small electric load devices, e.g. set-top boxes, routers, smart speakers). See table S1 in supplementary information (SI) for a detailed description of the categories and sources used.

To achieve a better representation of the regional diversity in the use of consumer goods, we expand the spatial resolution from two regions (Global North and Global South), used in the previous studies such as GEA and LED, to 11 regions. We follow the regional disaggregation of the world into 11 broad regions as defined in the MESSAGE model[2], resembling the classification commonly used by international organizations, including: Sub-Saharan Africa (SSA), Centrally Planned Asia and China (CPA), Central and Eastern Europe, Former Soviet Union, Latin America and the Caribbean (LAM), Middle East and North Africa (MEA), North America, Pacific OECD, Other Pacific Asia (PAS), South Asia (SAS) and Western Europe.

2.2. Modeling the demand, energy use and materials consumption of appliances

We estimate the energy demand from consumer goods through a Kaya equation, adapted to the analysis of appliances, following well-established practices in the field [40]. More specifically, for each year under consideration, we use the following disaggregation method by major group of appliances (i) and region (j):

$$\text{Energy demand (TWh)}_{ij} = \sum_{ij} h_j . \frac{n_j}{h_j} . \frac{u_i . W_i}{n_i} \quad (1)$$

whereas, energy demand is explained in terms of the changes in the evolution of activity and intensity. Activity is represented by the change in the number of consumer goods (n) or in the number of devices per household ($\frac{n}{h}$) times the number of households (h). Thus, alterations in activity can have two main sources: 'Demographic' for changes in the number of households (h), which in turn can evolve through alterations in the population (p) or in the average number of people per household (h' where $h = p/h'$); and a behavioral component 'ownership' for changes in the average number of devices per household (n/h). On the other hand, intensity is represented by the change in the energy consumption per appliance. Intensity can further be decomposed into two main terms: 'usage' (or load factor) for changes in the annual number of hours of use per device (u); and 'efficiency' for changes in the average power (or wattage) of the appliances (W).

In practice, we estimate the future demand of devices (activity) by category of consumer goods based on the per capita income in 2050. Income is a well-known driver of demand for appliances [4]. On the other hand, we empirically observe a high correlation between the current ownership of applications (i.e. number of devices per 100 persons) and the GDP per capita of the different regions in the world (R^2 = 92% of the simple bivariate model fit as reported in SI, section 3.1). Therefore, we compute the demand of appliances for each of the 11 regions, separately. This procedure takes into account

[2] https://iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html (last access 17 February 2023).

the regional differences in the per capita income, which is more consistent with the conceptual and empirical evidence. We use the projections for GDP and population in 2020 and 2050 that are available in the IPCC's shared socioeconomic pathways (SSPs) database [41–45]. (See a detailed explanation of the estimation in the SI, section 3.1 and appendix 2.) We model eventual saturation effects separately, as described in the presentation of the demand generator.

The base projections consider the trends observed in energy intensity over time. We revise the estimates for the energy efficiency of appliances in 2020 that were made in LED [3] and in GEA [34] based on the most recent evidence. Data is available for several types of appliances particularly in Europe and Japan [e.g. 15, 46]. In addition, we assume the same improvements in the energy efficiency of appliances between 2020 and 2050 as in LED that have been widely scrutinized and accepted.

We model the technological changes in appliances induced by digital convergence and the sharing economy through (narrative-driven) alterations in activity and intensity that translate the structural changes. Structural effects deal with the changes in energy demand from service provision that come from the substitution of consumer goods like analogue by digital appliances with functional convergence (e.g. shift from radio set to sound system to smartphone), as opposed to efficiency improvement (e.g. better radios, better sound systems). More specifically, we model structural effects through the changes in the preferences of consumers in relation to 'ownership' (number of devices per household or n/h) and 'usage' (load factor or u) of consumer goods. We elaborate more on the estimation of the effects of the structural change in the section 2.3 'Demand generator'.

Finally, we analyze the effects of the demand of appliances on material requirements in terms of both the total stock of materials and the annual material flows. Material stocks refer to the inputs that are necessary to produce the entire number of appliances in use at each moment. To estimate the material impact of appliances especially in 2050 that is very uncertain, we use the robust relationships found between the weight and the wattage ($R^2 = 52\%$), as well as between the weight and the volume of appliances ($R^2 = 85\%$), for a sample of representative devices of each type of appliances (see figure S6 in SI). Based on these strong correlations and on the evolution of efficiency and wattage, we derive the impact on material needs. For example, for the material weight, we use the correlation to estimate the average weights per type of device, by region; Then we multiply these coefficients of 'material intensity' by the stock of devices (per appliance and per region) to obtain the total weight of the material requirements.

Annual material requirements refer to the quantity of inputs needed to produce the new devices that both satisfy the new demand and substitute the old ones arriving to the end of the lifetime. We estimate the annual flows based on the total material requirements (as calculated in the previous step) and well-established estimates of the economic lifespan of the appliances that are obtained from the literature (see SI, table S2, for more details on the assumptions concerning the lifetime of devices).

We further compute the effect of the demand of devices on the main materials. The shares of the main materials (steel, aluminum and plastics) come from the analysis of the bill of materials of typical products that are provided by the manufacturers, following common practices in the literature [e.g. 16, 17, 47, 48]. In addition, we calculate the embodied energy of the appliances. This includes the energy required for raw materials extraction and for manufacturing, while excluding transportation. For that, we base our calculations on the estimates per type of technology that are available in the literature (see the inputs used in the material analysis in the SI, appendix 4).

2.3. Demand generator

We develop a demand generator with parameterizable key inputs to simulate the demand of consumer devices. The analysis allows the estimation of the effects of the change in different variables to reduce energy demand and materials consumptions from consumer goods, between 2020 and 2050, thanks to a new interactive Excel-based spreadsheet (see more details in the SI, appendix 5).

The spreadsheet includes an interface in which users can parameterize the main variables affecting the future demand of consumer goods. The interface allows to setting up assumptions for the Global North and the Global South separately, given the different dynamics of demand undergoing in these regions. Users can change the assumptions concerning the main aggregated variables affecting demand (activity) such as population, mean household size and income (GDP per capita). Concerning the latter, they have further the option to set a rate of decoupling between the growth of GDP per capita and demand for appliances to account for eventual effects of saturation.

More specific parameters concerning normative, behavioral and technological change are also customizable. The interface enables the parameterization of DLS in terms of the number of devices per capita (or by household depending on the nature of the appliance). Users can also define the maximum potential for digital convergence and sharing to reduce the number of devices and lower their energy intensity, in both the residential and commercial sector. As for sharing, in particular, users can additionally define different assumptions for key demographic variables such as the weight of urban population in 2050 or the share of population below 30 and above 65 living in shared spaces (co-living) in the year 2050.

Energy intensity and material intensity are both realistic and adjustable. We assume improvements in energy efficiency of 2.6% a year in the Global North and 3% in the Global South. These rates are close to the efficiency improvements of 2% a year observed in appliances over the past two decades [15], and less stringent than the 4% a year assumed in the Net Zero Scenario of IEA for the period between 2020 and 2030 [49, 50]. Users can therefore set higher (lower) efficiency improvements to compensate for a lower (higher) assumptions concerning the number of devices saved through digital convergence or sharing.

Finally, users can adjust several assumptions concerning the variables affecting material intensity. These include general parameters, such as the rate of decoupling of materials consumptions growth and respectively population growth and GDP growth. It also includes the possibility of adjusting specific variables concerning the annual rhythm of dematerialization (more specifically, the reduction of material weight per devices' wattage) or the lifetime of appliances. The spreadsheet can be provided upon request and reasonable justification.

3. Results

3.1. Demand of devices

We simulate the effects of digital convergence and sharing in promoting widespread access to consumer goods and reducing energy demand (see section 2 and SI for all calculations, assumptions, and data sources). Our analysis departs from the LED scenario [3]. Departing from such a scenario turns the reduction of the energy demand from consumer goods more challenging, even if LED estimates their final energy demand will increase 15% in 2050. We updated the estimates for the stock of appliances in 2020 with real data, taking more device categories into account (see SI, section 3.1). We also adjusted the projections for the number of appliances in 2050 by calibrating with the differences in per capita income among 11 regions (idem). This allowed a better estimation of the number of appliances in 2050 at 191 billion (+177% from 2020). These appliances would use roughly 13 000 TWh, assuming trends in efficiency improvement similar to those in the LED scenario.

We estimate the number of devices needed to provide DLS for all. This would require 8 billion devices in addition to the base estimate for 2050, distributed among the Global South regions as shown in figure 1. The most needed appliances are for food preparation (stoves, ovens) and thermal comfort (portable air conditioners). The regions with the greatest needs are SSA, SAS, and LAM, where half of the world population is expected to live in 2050 (figure 2). The needs of appliances vary with the region, from those for which scarcity is distributed across all categories (e.g. SSA) to those regions for which the need is more concentrated on thermal and food preparation (e.g. Other PAS) (figure 1).

3.2. Effects on energy and materials demand

Figure 3 show the effects of digital convergence and sharing on appliance numbers and energy demand. Digital convergence reduces the global number of devices in a way that more than compensates for the impact of providing enough energy services (lighting, communication, etc) to ensure DLS for all in 2050 (figure 3, top panel). Digital convergence also partially mitigates the estimated growth in the number of devices from 2020 to 2050, and sharing further reduces the number of devices in use in 2050. Overall, digital convergence and sharing limit the growth in the number of devices to 135% (instead of 177% in the base estimate for 2050).

Sharing devices has double the effect of digital convergence on lowering energy demand (figure 3, left-hand panel). Sharing devices such as washing machines and electric ovens instead of owning them increases the efficiency of providing services such as laundry washing or food preparation several times over. In fact, despite their higher energy intensity (which is assumed to double, at least), shared appliances replace several individually owned devices. As a result, sharing has a greater effect than digital convergence on reducing the energy demand per service provided. Overall, sharing and digital convergence together mean that a higher number of devices in operation in 2050 use 28% less energy than in 2020.

Sharing and digital convergence reduce the material needs of consumer goods. Compared with the levels in 2020, they lower the total material use by 21% in 2050 (figure 3, right-hand panel). This reduces the annual replacement flux by 34%, to 33 million tons in 2050, and embodied energy by 38%, to 2784 TJ (see the SI, sections 6 and 7, for analysis of the material impacts). Additional solutions can reduce the material requirements of consumer goods even further. Extending goods' average lifetime by 25% (i.e. one extra year every fourth year of lifetime) would reduce annual replacement flux by 47% (13 percentage points more), *ceteris paribus*. Similarly, reducing the weight of devices by another third lowers annual replacement flux in 2050 by 53% (roughly 20 percentage points more). These solutions could amplify the benefits of digital convergence and sharing in lowering the cost and carbon emissions of devices. Higher reductions in the number of devices are related to more savings in materials and energy, especially for larger regions (figure 3, down panels).

3.3. Socioeconomic gains with environmental co-benefits

How do digital-enabled innovations provide benefits to society, including widespread access to appliances and climate mitigation? Digital convergence and

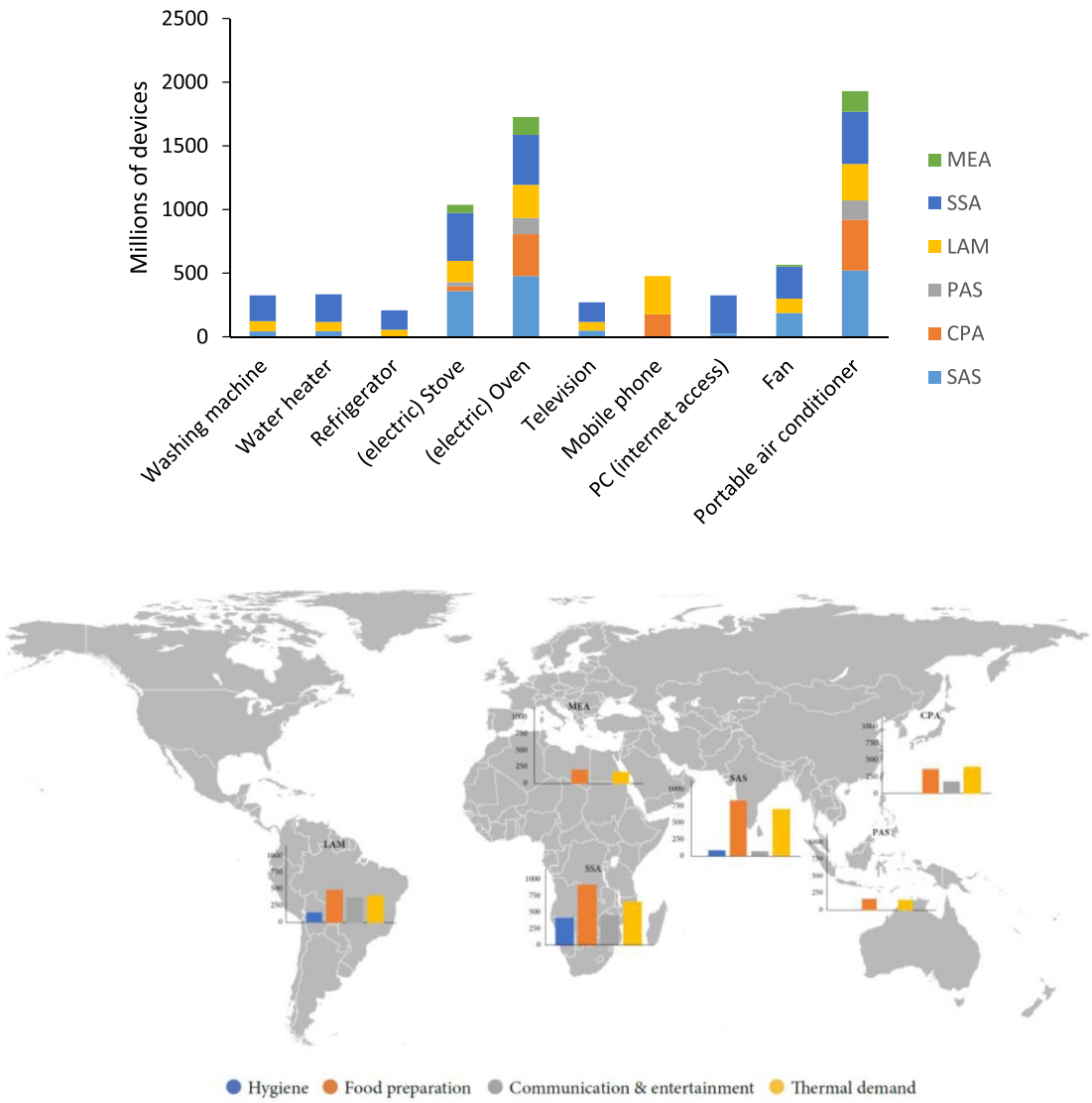

Figure 1. Number of devices needed to ensure decent living standards (DLS) in 2050 by regions of the Global South, in millions. Regions shown comprise Sub-Saharan Africa (SSA), Centrally Planned Asia and China (CPA), Latin America and the Caribbean (LAM), Middle East and North Africa (MEA), Other Pacific Asia (PAS), and South Asia (SAS). The different categories of devices are: hygiene (washing machine, water heater); food preparation (refrigerator, electric stove; electric oven); communication, entertainment & productivity (television, mobile phone, PC); thermal demand (fan, portable air conditioner). The graph below shows the breakdown of devices by regions, in million units.

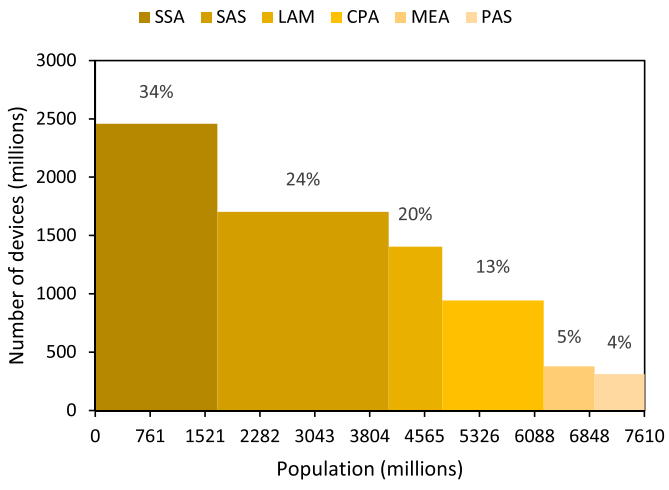

Figure 2. Number of devices needed to ensure decent living standards (DLS) in 2050 by regions of the Global South, in millions.

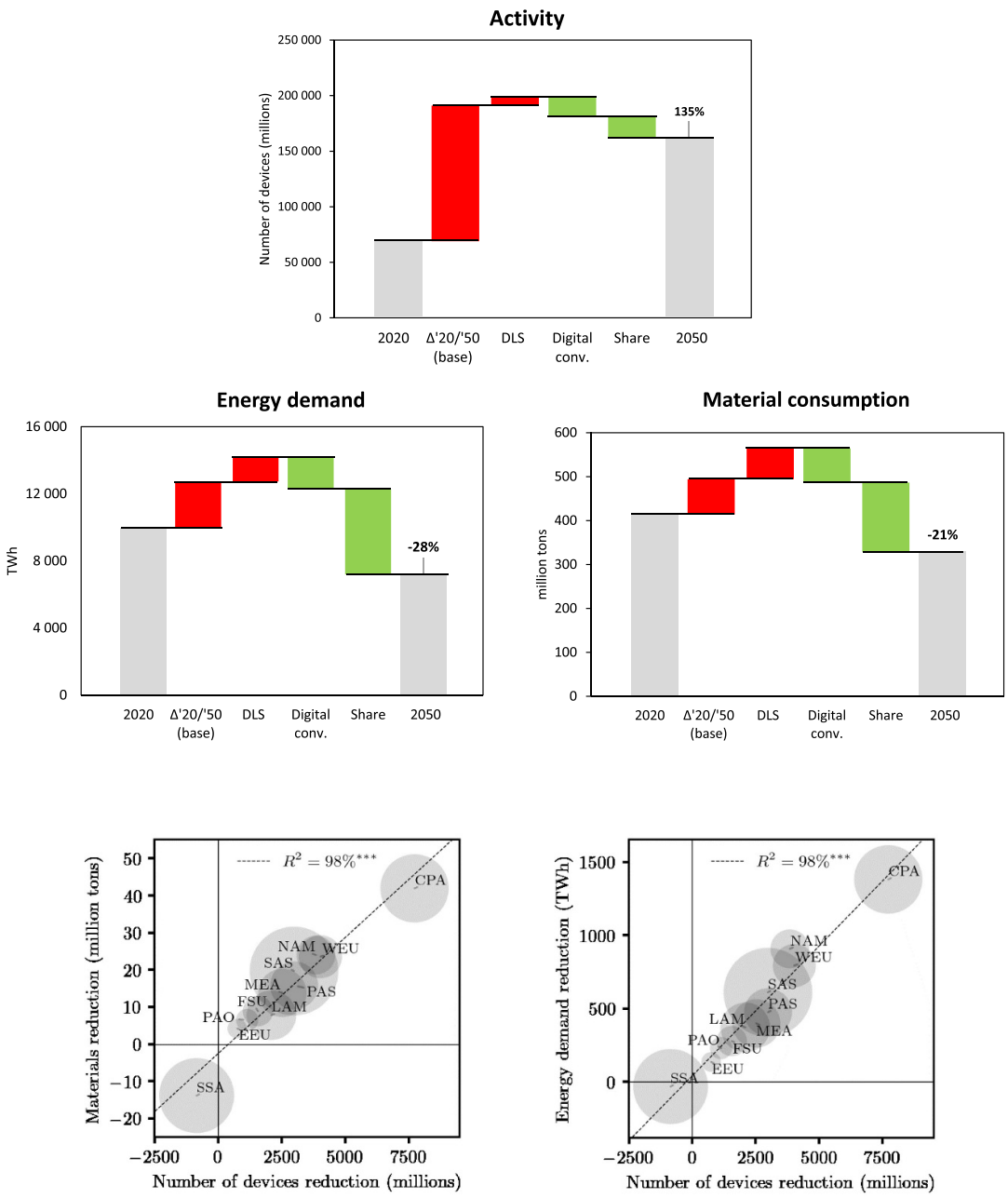

Figure 3. Effects of DLS, digital convergence, and sharing on the number of appliances, energy demand and material consumption from appliances in 2050 (top), and bivariate relation between activity and dematerialization (down-left) and activity and energy demand (down-right), by region. The size of the points is proportional to the population in each region.

sharing improve access to essential services provided by appliances (e.g. food preparation, communication, entertainment). On the one hand, digitally convergent innovations such as smartphones make several standalone devices redundant (e.g. alarm clocks, GPSs, pocket torches). On the other hand, sharing instead of owning lowers the barriers to low-income families accessing larger and more expensive devices such as washing machines, water heaters, or refrigerators. Under the scenario outlined here, there are 8 billion more devices (+6%) in the Global South than in the base case. By 2050, the number of devices per capita in the Global South increases by +200% to 16, narrowing the gap with the Global North.

Digital convergence and sharing make the widespread of DLS more feasible and accessible. We estimate that digital convergence and sharing together would save 29 billion devices (−15%) by 2050, corresponding to a saving of 9 trillion US dollars (−39%) at current prices.

New production practices and the use of more efficient appliances have positive effects on the environment. Compared to the base estimate, direct energy demand is reduced by 5547 TWh (−44%) by

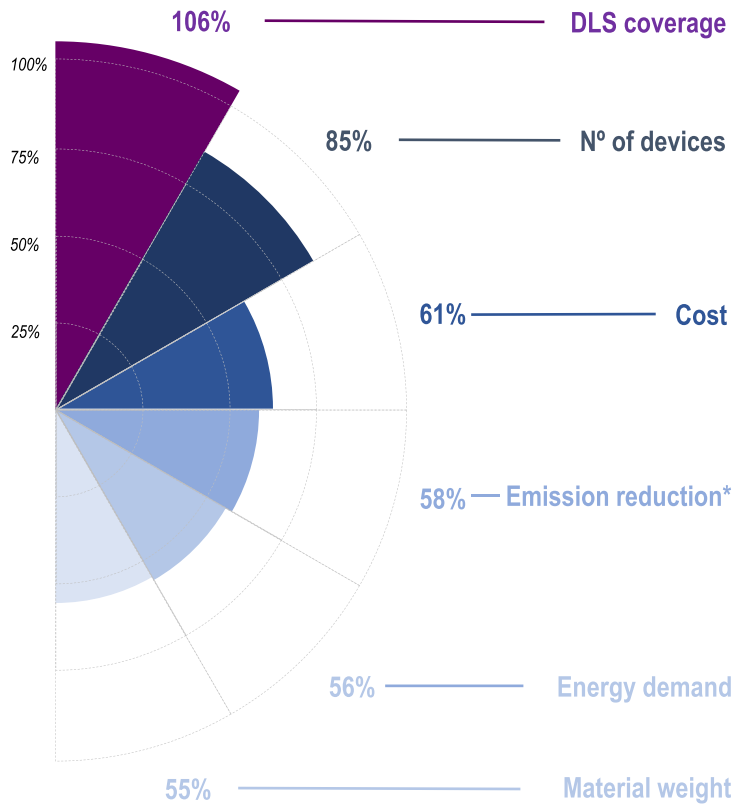

Figure 4. Social gains of digital convergence and sharing in appliances with decent living standards, in comparison with the base estimate for 2050. Index (100 = base estimate). Lower is better, except for DLS coverage, for which a higher value represents more social benefits. (* in relation to the emissions in 2020 and calculated by using the regional carbon intensities of electricity for that year).

2050 (cutting 42% of GHG from consumer goods in relation to the levels in 2020). In addition, annual material consumption falls by 45% to 33 million tons/annum. Figure 4 summarizes the social gains of digital convergence and sharing in appliances.

4. Conclusions

Consumer goods are increasing energy demand and contributing to further augment the share of household consumption in global GHG that is already responsible for more than 60% of emissions [51, 52]. This increase has been accelerated by the effect of the rising incomes in developing countries, more recently. Digitally-enabled innovations that enhance functional convergence and the sharing economy have the potential to raise the standards of living in low income countries without increasing the pressures in the environment. The analysis shows mechanisms, such as social and technological innovations, that can promote development and reduce GHG emissions. The effects of these mechanisms had not yet been studied in the literature [9], which has focused more on other factors such as the role of income in reducing emissions in the Kuznets Environmental Curve [53, 54].

These results have significant implications for policymakers. They demonstrate that there is a better way to organize the delivery of modern energy services—one that provides access to consumer goods more rapidly and efficiently, and at a lower cost. This shows once more the benefits of more granular approaches to climate mitigation [55, 56]. Public policy could tap into the opportunities opened by digital convergence and sharing by ratcheting up efficiency standards—especially in the Global South. Policymakers could also address more specific obstacles to the growth of sharing economies (e.g. promote the use of shared equipment in buildings) or of innovations in digital convergence (e.g. reinforcing electricity reliability; promoting affordable high-speed digital connectivity; enabling the dissemination of multi-functional equipment such as smartphones or tablets to replace small and large devices like TVs).

This analysis opens new perspectives for future research. Our approach builds on trends observed in consumer goods and estimates the effects of their dissemination. Future research could shed more light on the technological changes expected in appliances. Particularly, it could identify the full range of digitally convergent and sharing innovations that will be available in the short term. In addition, this study shows that improving the life of the most deprived

does not lead necessarily to higher carbon emissions, relativizing previous results [e.g. 57]. It also illustrates the potential of granular demand-side innovations to improve quality of life and mitigate climate change, applied to consumer goods, in line with recent results [e.g. 58–60]. Future work could extend this analysis to other sectors (e.g. mobility, industry), as well as investigate the effect of the impact of disparities on the access to DLS.

A current debate questions the effect of digitalization on the growth of consumption, as well as of information and communication technologies (ICT) emissions and its part of global GHG emissions [e.g. 31]. The ICT's share of emissions is estimated between 1.8% and 3.9% [16]. Some studies emphasize the role of efficiency improvements in stabilizing the emissions from user devices, networks and data centers, and link ICT emissions to the number of users which will naturally saturate [25, 61, 62]. Others project that ICT emissions will increase as a result of slowing down efficiency improvements (as Moore's law reach physical limits) in network and data centers, as well as estimate a growing embodied energy associated with the dissemination of devices (including IoT) [63, 64]. However, these emissions should be compared with the ICT impacts on the rest of the economy. ICT will enable carbon savings in other sectors [65, 66], but some authors argue that it can increase global emissions as efficiency gains will lead to consumption rebounds and growth in other sectors (Jevons' paradox) ([67], see [68] for a critique of this argument). Overall, large uncertainty remains on the net effect of ICT on climate change. Similarly, new forms of deregulation or of promoting conspicuous consumption (e.g. some houses or rides schemes are more commercial exploitation than sharing) may limit the potential of sharing economies to improve sustainability [27, 69]. Other factors can limit the dissemination of sharing (e.g. a lower propensity of sharing in more affluent users [70]) or restrain the effect of sharing on reducing energy and materials demand through rebounds in consumption (income effect) or production (higher turnover of the shared products [71]). More research is needed to understand the extent of these effects in appliances. The role of social and technological innovations such as digitally-enabled functional convergence and sharing economy is relevant in these debates as they can increase the direct use of energy and materials, but also open promising avenues to significantly decrease global GHG emissions and to democratize the access to essential goods and services.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Supplementary Information

The potential of digital convergence and sharing of consumer goods to improve living conditions and reduce emissions

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1. INTRODUCTION

The growing demand of consumer goods[1] increases the pressure on material consumption while putting at risk the efforts to limit global warming to 1.5ºC. Appliances are among the fastest growing categories of energy demand, driven by increase in revenues and rising ownership of devices (Gertler et al., 2016). They already account for 15% of global final electricity demand, or one-third of the energy consumed in buildings if lighting and cooking is included (IEA, 2017a). If demand keeps increasing at the same pace, overrunning the improvements in energy efficiency, one out of six units of final energy demand in 2050 will go to consumer goods (i.e. appliances and electric plug-loads), even in a low energy demand scenario (Grubler et al., 2018). This would put at risk the efforts to reduce the energy consumption in buildings, which already account for 60% of global electricity demand, corresponding to 28% of global energy-related CO_2 emissions in 2019 (IEA, 2020a).

New technological and social innovations open opportunities to conciliate the higher demands for consumer goods with the decarbonization targets. Two trends are particularly promising to reduce the energy demand from appliances, without lowering the provision of energy services (e.g. communication, entertainment, cool and heating): digital convergence and sharing economies.

Digital convergence refers to the tendency of stand-alone objects to converge onto new devices, creating hybrid "multifunctional" objects (Bainbridge & Roco, 2016). The typical example is the smartphone that converged previously unrelated technologies such as the telephone, television and computer through an increasing interplay of shared parts consisting of digital electronics and software including applications or “Apps”.

Sharing economy denotes the case in which an otherwise underutilized good or service, such as cars or devices, is used by multiple people, as opposed to its ownership for individual consumption. Moving from owning to sharing presents several benefits such as more intensive use of the good or service, waste minimizing (circular economy) and reduction in the material needs (dematerialization).

[1] Consumer goods are by definition products that consumers buy to perform one or several services (lighting, cooking, entertainment, etc.) for their own (direct) use, as opposed to capital goods that are mainly used in business. They can include all sort of plug-loads in buildings that are not fixed and dedicated to thermal comfort. Large and small household appliances, such as refrigerators and radio alarm clocks respectively, are a major group of consumer goods. For this reason, in the rest of this paper, we will be referring to these goods interchangeably as consumer goods, appliances, equipment or devices.

Sharing economy and digital convergence can therefore contribute to significantly lower the demand of consumer goods. They open promising avenues to lower both the energy demand and the material consumption from appliances. The environmental benefits could be of several orders of magnitude by service provided, largely compensating any possible rebound in consumption (Sorrell et al., 2020). More importantly, digital convergence and sharing could enable the widespread access to the services provided by modern consumer goods (entertainment, communication, lighting, etc.), particularly to the population in developing countries where their access is more limited today.

The purpose of this research is to estimate the potential of digital convergence and sharing economy to reduce the energy demand from consumer goods and to dematerialization in 2050 for meeting the 1.5ºC target and the sustainable development goals.

We develop a scenario that satisfies the demands for consumer goods in 2050 while ensuring decent living standards for all. This scenario reduces their energy demand by roughly a third and the material consumption by a fifth relatively to 2020. The results contribute to identify strategies that drastically lower the energy and material requirements from consumer goods. The analyses identify the categories of appliances with the highest potential for energy and material reductions. The regional disaggregation reveals the areas that will contribute the most for the growing demand of consumer goods, and thus should receive more attention. Finally, and more importantly, the results show that digital convergence and sharing can counteract the increase in energy demand of consumer goods from raising revenues and the provision of decent living standards, with lessons for other sectors.

The supplementary information proceeds as follows. Section 2 presents the emerging trends in consumer goods. Section 3 shows the methodology adopted in this investigation. Section 4-6 present the results of the simulations, under the different scenarios, for the number of appliances, energy demand, and material consumption. Section 7 shows the effects of alternative assumptions for the evolution of the material intensity of appliances in the material use. Section 8 concludes with a discussion of the main results and their implications for sustainability.

2. EMERGING TRENDS IN CONSUMER GOODS

We identify and review four main trends that are emerging around consumer goods, in an increasing order of disruptiveness: long-term efficiency improvement; economic and structural change; digital convergence; sharing economies.

2.1. Long-term efficiency improvement

The energy use by most appliances in buildings has considerable decreased over time. This happened thanks to the continuous improvements in the quality and performance of the products that has enhanced the equipment efficiency. Efficiency gains are around 40% for large appliances in the past three decades (Enerdata, 2020). Ratcheting minimum energy performance standards (MEPS) for appliances played an important role in this trend. MEPS cover now 80% of several large appliances like residential refrigerators in more than one hundred countries (IEA, 2021). For example, new refrigerators sold in Europe have to be 75% more efficient than a decade ago.

The efficiency gains in appliances have been counterbalanced by the rapid growth in small electric plugs whose demand is driven by revenues increase and rising ownership of devices (IEA, 2021). This has limited the decoupling between the energy consumption and the increase in the number of devices.

2.2. Economic and structural change

As for other sectors, changes in energy demand from consumer goods can be disaggregated into changes in activity, intensity and structural effects (Koomey et al., 2019). Activity is largely influenced by economic factors, such as substitution effects from changes in the relative prices of consumer goods, and income effects from lower prices or increasing available revenue of the families. Intensity of consumer goods depends on the evolution of the power unit consumption or efficiency per device. Efficiency improvement is an important trend in consumer goods, what is covered in Section 2.1. Finally, structural effects relate to changes in the weights of the categories of consumer goods, reflecting alterations in the patterns of consumption. Structural effects have been largely overlooked in the literature which has been focusing on the first two effects.

Structural effects refer to the impact produced by changes in the relative activity or numbers of the composing categories of consumer goods. In the extreme case, this could explain the paradox under which the overall energy demand from consumer goods reduces even if the consumption of a large number of categories increases.

Several factors explain the changes in the structure of consumer goods. Since structural effects depend on changes in the relative demand for each category, it is influenced by the same economic and technological effects that affect the activity for these categories in the longer run. Therefore, we can again distinguish a substitution effect and a revenue effect.

The substitution effect leads to a relative increase in the share of consumer goods for which prices reduce faster than the average. For example, the price of household appliances has been decreasing in the past decades, as shown in the 25% percent reduction in the harmonized index of consumer prices for household appliances in the European Union (Figure S1). Particularly, the price of electronic equipment has decreased faster than the rest of household appliances, as proxied by the producer price index in the United States (Figure S2). This explains the general increase in the share of electronic goods in the structure of consumer goods.

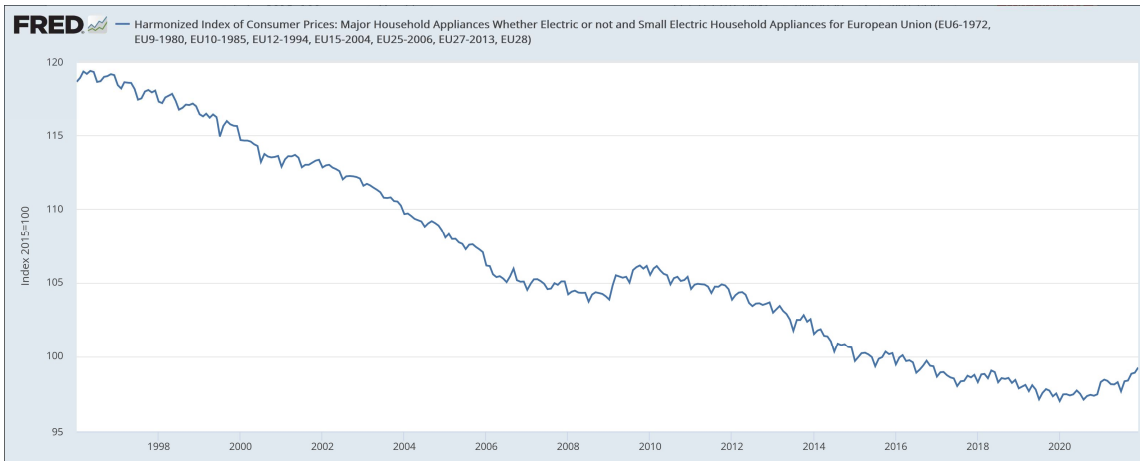

Figure S1. Harmonized Index of Consumer Prices of household appliances in the European Union, 1997-2021.
Source: Eurostat: Major Household Appliances Whether Electric or not and Small Electric Household Appliances for European Union (EU6-1972, EU9-1980, EU10-1985, EU12-1994, EU15-2004, EU25-2006, EU27-2013, EU28) [CP0531EUCCM086NEST], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/CP0531EUCCM086NEST, January 21, 2022.

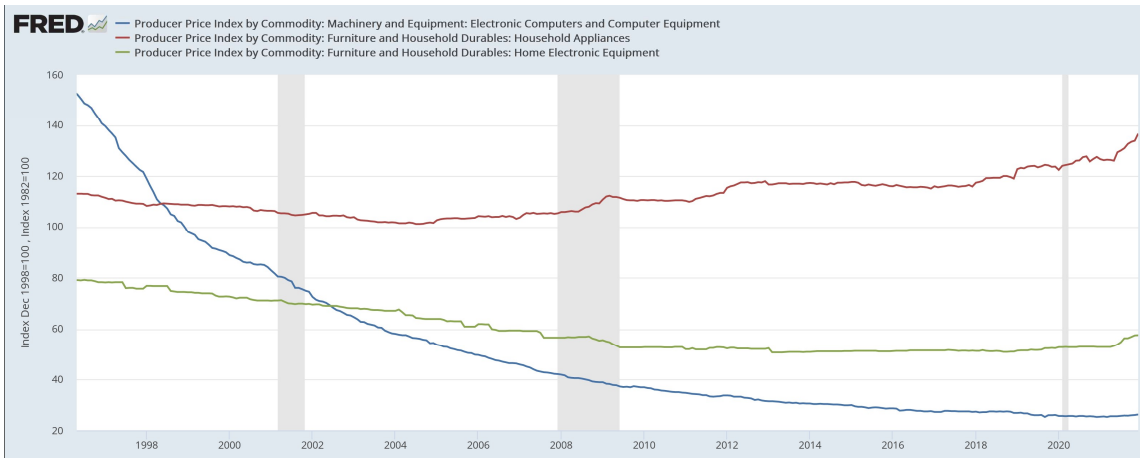

Figure S2. Producer Price Index by Commodity in the United States, 1997-2021. Source: U.S. Bureau of Labor Statistics, Producer Price Index by Commodity: Machinery and Equipment; Electronic Computers; and Computer Equipment [WPU115], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/WPU115, January 21, 2022.

The income effect results from the increase in the disposable revenue of the families following the decrease in the prices of consumer goods and/or the increase in general revenues (e.g. salaries) in real terms (after inflation). The income effect increases the consumption of all type of goods. These include more expensive, larger household appliances, which become more accessible in low-income countries in the Global South. The final effect will depend on the relative strength of these two effects. For example, if the income effect is too strong in low-income countries (with low rates of appliances ownership), one could expect an increasing share of larger appliances which have higher energy consumption.

Structural effects therefore capture substitution effects within service categories, e.g., from radio sets to mini stereo or from feature phones to smartphones. But they also include structural shifts across device categories from basic provisioning (decent living standards) to luxury items, e.g., from fans to A/C units in thermal comfort, or from hand washing with hot water (boiler) to washing machines and dryers. These structural shifts have implications in energy demand and materials use.

2.3. Digital convergence

Digitalization offers new opportunities to reduce the effects in energy, resources and emissions across the main dimensions of consumption (mobility, homes, food, energy). Digitalization impacts an increasing number of domains of social life by reorganizing them around digital technologies and media infrastructures (Brennen & Kreiss, 2016). The transition

from analog to digital technologies (post mail to email, telephone call to chat) changes the way that people interact in the spheres of work or leisure (Bradley, 2017). Digital technologies are also transforming the organization of activities and business by blurring the digital and physical worlds (Gartner, 2021). Applications or “Apps”, for example, perform specific functions (tasks or services) without the need for further separated information and operational technologies.

Digital convergence is another megatrend that refers to the tendency of stand-alone objects to converge onto new devices, creating hybrid "multifunctional" objects (Bainbridge & Roco, 2016). Digital convergence can be a powerful lever for lowering energy demand and material use. This is a new topic of research that was largely put forward in Grubler et al. (2018) with the illustrative example of the substitution of physical devices by “apps” running on smartphones. Smartphones can substitute at least seventeen devices, from alarm clock to GPSs and radios, using only 2.5 watts on standby and 5 watts in use. This is thirty times less the power in standby and hundred times less the power in use that would be need by that many replaced devices (Grubler et al., 2018). Smartphones still remain ten times more efficient in service provision (in terms of energy use) when discounting the energy demand from the supporting digital infrastructure (Bento, 2016).

As for the impact on materials use, digital convergence can achieve a factor of 25 reduction in the embodied energy (including the avoided transformation of raw materials) necessary to produce the devices that have become redundant (Grubler et al., 2018). Figure S3 summarizes the contribution of smartphones for dematerialization and lower energy demand. This illustration shows the potential of digital convergence to reduce both the energy intensity of the services provision and the number of devices in use (dematerialization).

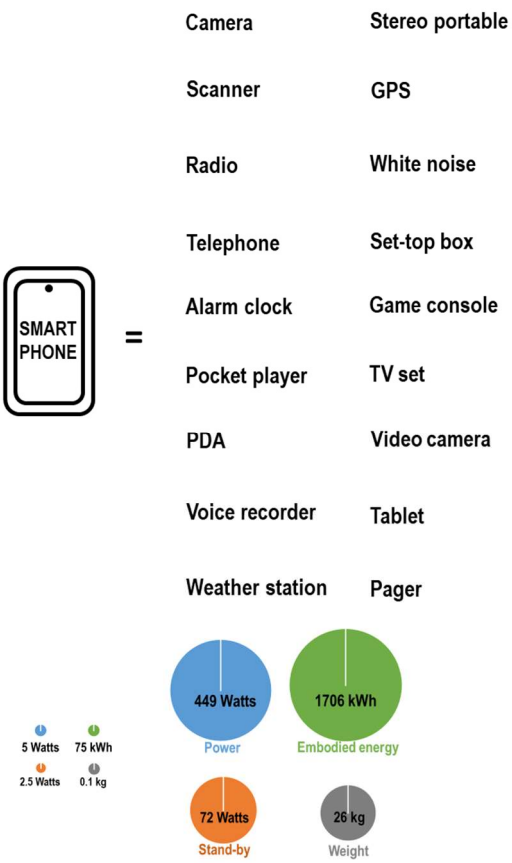

Figure S3. Digital convergence and dematerialization: illustrative example with the smartphone.

Data sources: Grubler et al., 2018; Bento, 2016.

Electronic consumer goods need relatively more energy in production than other consumer goods (ADEME, 2019). Smartphones are very efficient in operation with direct energy consumption corresponding to only 3% of the overall energy impact. But 97% of the impact of smartphones comes from the embodied energy, i.e. the energy necessary to produce the materials which enter into their production. These numbers compare with 63% (direct energy) and 37% (embodied energy) in the case of a typical refrigerator (Figure S4). However, the total energy demand can still be significantly lower in small electronic goods such as smartphones than in refrigerators, even if adjusted for the shorter lifetime of the formers (3 years instead of 15 years for fridges).

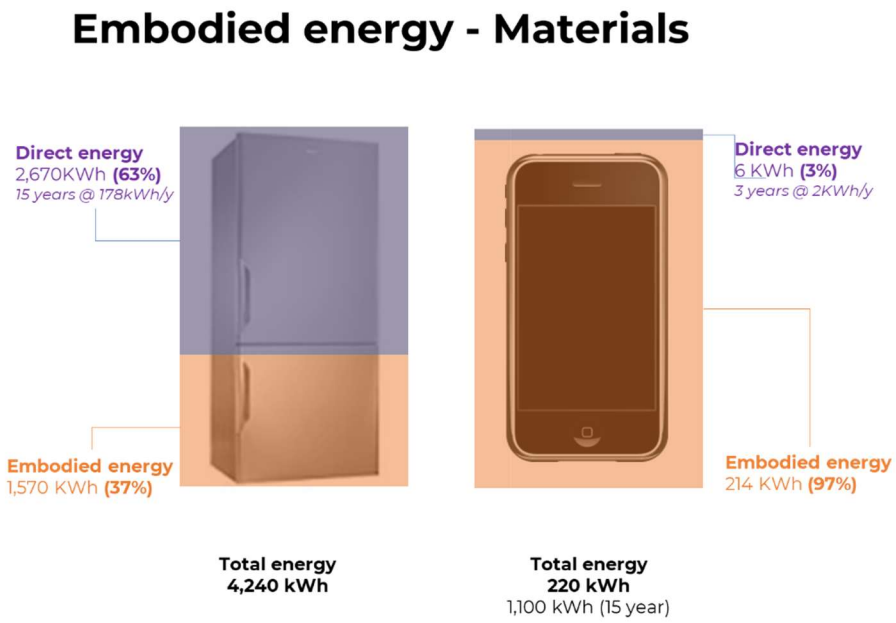

Figure S4: Comparing direct and indirect (embodied) energy of a refrigerator versus mobile phone.

Data sources: Direct energy: Refrigerators - McNeil et al. (2008), GEA (2012), IEA (2012b); Mobile phones - Bento (2016). Embodied energy: Refrigerators - Boustani et al., 2010; Mobile phones - Babbitt et al., 2017.

The literature is scarce on the effects of digitalization on energy demand. IEA (2017b) concludes that the digitalization impacts can significantly change within scenarios and across energy demand sectors (transport, buildings and industry). Another rare study, Wilson et al. (2020) surveys the literature about a number of digital innovations across several domains (mobility, food, homes and energy). The authors show evidence of a clear potential of digital consumer innovation for emission reductions. However, they also point to some studies that indicate possible demand increases due to rebound effects and substitution effects.

2.4. Sharing economy

Sharing economy is a complex phenomenon which in the last decade has been able to influence not only worldwide customers behavior but also incumbents' business models and their profitability (Gislon, 2020). The sharing economy is a peer-to-peer activity that allows people to share or obtain goods and services, often through online platforms.

Sharing is the main principle. It refers to the case in which a good or service, such as cars, houses or devices, is used by multiple people, as opposed to its ownership for individual consumption. Moving from owning to sharing presents several benefits such as more intensive

use of the good or service, minimizing material needs (dematerialization) and waste (circular economy).

Single-owned devices are often underutilized. For example, a privately owned car is typically parked the largest part of its lifetime. This fact together with the increase in congestion in the cities has increased the interest for shared mobility services over personally owned transport modes. Mobility-as-as-Service or simply MaaS is an emerging concept which concentrates multiple mobility services (of different types and providers, both public and private) in a single platform (most often, a journey planner) where users can create and manage their trips. MaaS encompasses a wide range of emerging mobility services, from sharing the rides (e.g. carpool) to the means (bicycle-, scooter-, car-sharing) or even shared (mini)buses. As for the later, in a study for the city of Lisbon, ITF (2015) has estimated that the deployment of shared mobility (cars and mini-buses) could reduce a large number of cars (to 3% of the today's fleet) and congestion. It has been estimated that almost 2 million cars were not sold in 2016 in the world due to ride-sharing apps, with particular impact in China (960 thousands) and India (540 thousands) (Statista, 2022). The number of users of shared mobility has been increasing even during the pandemics and reached 44.2 million in car sharing, 49.3 million in e-scooter sharing, and 669.3 in bike sharing in 2020 (Statista, 2021).

Sharing allows more intensive use of houses as well. As of 2019, Airbnb has served 500 million people with over 6 million Airbnb listings in more than 191 countries and regions. Peer-to-peer accommodation platforms such as Airbnb have become an important part of the tourism and hospitality industry, replacing to some extent the need for the construction of additional hospitality capacity (Zhang et al., 2020).

Sharing improves efficiency and reduces the costs of the use. Sharing, rather than owning, appliances and services allow that devices can be used more intensively, at a higher load factor, more often. Thus, shared devices can run more efficiently at the lowest energy consumption and operational cost (Ivanova et al., 2020). Several devices are increasingly shared at the buildings or community levels. For example, washing machine rooms are not unusual in multifamily buildings in North America and increasingly in Europe and other parts of the world like. Likewise, laundry shops become common in many cities of the world. Another example is the increasing centralization of equipment such as Heating, Ventilating and Air Conditioning (HVAC) systems at the building level. Sharing has the potential to reduce the

number of devices by centralizing equipment (e.g. washing machines, water heaters and ventilation).2

Sharing instead of owning reduces material requirements. Sharing reduces the number of devices that are required to serve the same service (lighting, entertainment, hygiene, etc.). By lowering the number of devices through their collective use, sharing has the potential to reduce the embodied energy associated to the avoidable goods (Ivanova et al., 2020). In so doing, sharing contributes to reduce the number of devices that have to be produced and disposed at the end, relieving the pressure on waste management and recycling. Overall, sharing lowers the direct and indirect emissions of the devices.

Co-living, co-working and shared building infrastructure are other types of flexible usage that are representative of sharing. Co-living is the most common way of sharing. A five or more average household in EU has half of carbon and energy footprint that of a one-person average household (Ivanova & Büchs, 2020). Collective living or working improves the possibility that people share more amenities such as lighting, space heating/cooling, living spaces, appliances and other equipment (Ivanova et al., 2020; Fremstad et al, 2018; Wiedenhofer et al., 2018). Collective living (including renting out guest rooms) reduce in average 0.3 tCO2eq/cap per year (Ivanova et al., 2020).

The few number of studies we found that estimate the benefits of sharing (e.g. Ivanova & Büchs, 2020; Fremstad et al., 2018) use statistical and econometric analysis of household surveys (e.g. Household Building Surveys from Eurostat, US Consumer Expenditure Survey), crossed with estimates of the products' energy and carbon footprint calculated, for example, from input-output databases (e.g. EXIOBASE).

The studies tend to analyze the potential of sharing in terms household economies of scale, as well as on the relation between household size and density (see a review in Ivanova & Büchs, 2020). Adding one person more to a one-member household can significantly reduce the energy consumption and material footprint, however the marginal gains of further increases become much smaller. After some threshold, the economies of scale may exhaust, and thus increases in the size of the household implies reinforcement in lighting, HVAC, appliances, water supply, among others. On the other hand, more densely populated and compact urban

[2] We were unable to find estimates for the carbon reductions obtained by sharing equipment (HVAC, washing rooms, etc.), instead of single-owned by the household, at the building level. The benefits of sharing equipment in multi-family or multipurpose buildings enter in the studies that compare the energy and carbon footprint in urban areas and rural areas through the general concept of household economies of scale. Still there is no explicit estimation of the potential of sharing equipment for reducing the energy demand of buildings.

areas tend to be regarded as presenting higher opportunities for resources sharing between households (Gill & Moeller, 2018). But urban areas also attract more wealthy population (Poom & Ahas, 2016), living in smaller size households (Ivanova & Büchs, 2020), that counterbalance the effects of density. Thus urban areas can present household economies of scale that are lower than in suburban areas (Ottelin et al., 2015). Several empirical studies show lower potential for further household economies of scale in urban contexts compared to rural areas, though with lower emissions per capita in the cities (e.g. Fremstad et al., 2018).

There is still a lack of systematic analysis of the way that new megatrends such as digitalization, dematerialization and sharing impact on the energy efficiency of the appliances and have the potential to shift demands across types of appliances with an effect in the overall energy demand.

3. ESTIMATING THE IMPACTS ON ENERGY DEMAND AND MATERIAL CONSUMPTION

The section starts by presenting the methods followed to estimate the demand for consumer goods, as well as the resulting energy and material implications, both in 2020 and in 2050 in the base (or reference) case (Section 3.1). Then we explain the calculations of the effects of generalizing decent living standards (Section 3.2), digital convergence (Section 3.3) and sharing the devices (Section 3.4).

3.1 Base case

We depart from the projections for the demand of consumer goods in the base year of 2020. These projections come from the GEA Efficiency scenario (Ürge-Vorsatz et al., 2012), which was recently re-estimated in the Low Energy Demand (LED) study (Grubler et al., 2018). Similarly to LED, we estimate the demand for appliances from both the residential sector and the commercial/services sector.

We estimate the demand by major types of consumer goods. Comparing to LED or GEA Efficiency, we consider a finer-grained categorization of the consumer goods into: hygiene (e.g. hot water, washing machine); food preparation (e.g. refrigerator, electric stove); communication & entertainment (e.g. mobile phone, television, personal computer); lighting (all types of lamps), thermal demand (e.g. fan, portable air conditioner), and miscellaneous (mainly consisting on small electric load devices, e.g. set-top boxes, routers, smart speakers). See Table S1.

Table S1. Consumer goods and key sources[3]

Appliance	*Category*	*Number of devices*	*Energy consumption*	*Service*
Lamps	Lighting	NAS, VITO	VITO, WB, Gifford et al.	VITO
Washing machines	Hygiene	Pachauri	McNeil et al., Ruedenauer et al.	EC, Ruedenauer et al.
Water heater	Hygiene	Pachauri, GMI	IEAa	IEAa
Refrigerator	Food preparation	Pachauri, EUI	McNeil et al., GEA	IEAb
Freezer	Food preparation	Pachauri, IEAb	IEAb	IEAb
Electric stove	Food preparation	Industry Research	WB	(various)
Electric oven	Food preparation	Amienyo et al.	WB	(various)
Television	Communication & entertainment	ITU, Pachauri	McNeil et al, GEA, WB	WB
Mobile phone	Communication & entertainment	ITU, Pachauri	Bento	GSM Arena, Bento
PC	Communication & entertainment	ITU, Pachauri	WB	WB
Fan	Thermal demand	Pachauri	WB, BRE, Cabeza et al, Radgen et al	BRE
Portable air conditioner	Thermal demand	Hitchin et al.	WB	BRE
Small electric load devices	Miscellaneous	EWEB	EWEB	-
Productive power and thermal	Productive uses	IEAc	IEAc	-

3 NAS-National Academies of Sciences, Engineering, and Medicine. 2017. Assessment of Solid-State Lighting, Phase 2. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/24619.

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To validate the estimates for the global stock of appliances in 2020, we compare with the actual numbers for the global stocks of major appliances (e.g. refrigerators, televisions, washing machines). Numbers of the stock of appliances in use are available from several sources, including the national statistics of the main regions such as the US4 and Europe.5 To highlight the different dynamics in the rising ownership of devices, namely from the wealthiest developing countries, we expand the spatial resolution to 11 regions from the 2 regions (global North and global South) in LED (Appendix 1).

The level of stocks of consumer goods (activity) here estimated serves as the basis for the estimation of the impact on the energy demand and on the materials consumption (the latter is explained below).

We use typical disaggregation analysis (à la Kaya) to derive the energy demand from consumer goods, by major group of appliances, and by region. More specifically, we consider the following disaggregation method:

$$\text{Energy demand (TWh)}_{ij} = \sum_{ij} h_j . \frac{n_j}{h_j} . \frac{u_i . W_i}{n_i}$$

for the consumer good *i* and the country *j*. We can recognize here two components:

- **activity**: changes in the number of consumer goods (*n*) or in the number of devices per household ($h . \frac{n}{h}$). Alterations in activity have two main sources: 'Demographic' for changes in the number of households (*h*) through alterations in the population (*p*) or in the average number of people per household (*h'* where *h=population/h'*); and 'Ownership' for changes in the average number of devices per household (*n/h*);

- **intensity**: changes in the energy consumption per appliance. Intensity can further be decomposed into two main terms: 'Usage' (or load factor) for changes in the annual number of hours of use per device (*u*); and 'Efficiency' for changes in the average power (or wattage) of the appliances (*W*).

4 e.g.: U.S. Energy Information Administration (2020), Office of Energy Consumption and Efficiency Statistics: https://www.eia.gov/consumption/residential/data/2015/hc/php/hc3.1.php (last access August 4, 2020).

5 For example, from the European Commission's EU Buildings Database: https://ec.europa.eu/energy/eu-buildings-database_en (last access August 4, 2020).

The base projections take into account the trends observed in efficiency over time. We revise the estimates for the energy efficiency of appliances in 2020 that were made in LED, which in turn updates the estimates in GEA (Ürge-Vorsatz et al., 2012), with the most recent data. Data is available for several types of appliances in Europe6 and Japan (METI, 2015). In addition, we assume the same improvements in energy efficiency of appliances between 2020 and 2050 as in LED.

As for the stock of consumer goods in 2050, we estimate the demand of devices based on the revenue per capita in that year. The base projections consider the historical relationship between the number of devices per 100 persons and the level of GDP per capita. Figure 1 shows the high correlation between applications ownership (i.e. number of devices per 100 persons) and the GDP per capita of the different regions in the world.

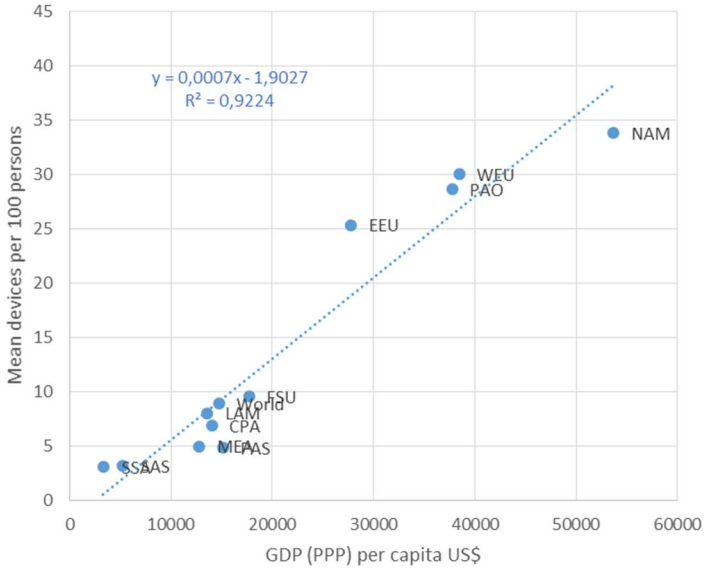

Figure S5. Correlation between the average number of appliances per 100 persons (including in the commercial sector) and GDP per capita, world and by region.

We start by computing the GDP per capita (at parity purchasing power, PPP), by main regions, using the projections for GDP and population in 2020 and 2050 that are available in the IPCC's Shared Socioeconomic Pathways (SSPs) database.[7] Then, we correlate the number of devices in use per 100 persons, per category, in 2020, with the GDP per capita by region. We take the

[6] e.g.: https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/trends-europe.html (last access August 4, 2020)

[7] SSP database hosted by the IIASA Energy Program at https://tntcat.iiasa.ac.at/SspDb (download in 15/10/2020).

best fits to estimate the number of appliances in use by category in 2050, taking into consideration the projections for the GDP per capita in that year from the SSPs database. We assume that the trend between revenue and device ownership remains stable over time. Appendix 2 lists the type of equation and the parameters assumed for the calculation of the number of devices (activity) by category in 2050.

This is an enormous improvement in the projections of the number of devices over previous studies. LED, for example, computes demand by using average ownership rates in only two regions (Global North and Global South). The present revision not only explicitly considers a larger range of devices as it computes the demand for appliances for the 11 regions, separately. It further takes into account the differences in revenue per capita, what is conceptually more correct.

We estimate the energy demand from consumer goods in 2050 based on the projections for the number of units and the assumption for the energy intensity, following the decomposition method presented above.

In parallel to the estimation of activity and energy demand, we also calculate the services provided by consumer goods as well as the ecological footprint. More specifically, we provide estimates for the level of energy services provided (billion lumens, thousand tons of washed laundry, etc.), material intensity (by weight and by volume), and annual material flows. The level of energy services is calculated by device using information about its average (annual) use (load factor) and the service performed by a typical model.

Material impacts are an important consequence of the increase in the demand for consumer goods. We analyze these impacts in terms of both stocks of materials and annual flows.

Material stocks refer to the inputs that are necessary to produce the number of appliances in use at each moment. We estimate the material requirements based on the high correlation observed between the wattage of the devices that are representative of each type of appliance and their weight (Figure 2, right-hand). We use this correlation to estimate the average weight per type of device. Then we multiply this (material intensity) by the stock of devices to obtain the total material requirements in terms of weight. On the other hand, the volume footprint results from the calculation of the typical volume of the devices by using the correlation with their average weight (Figure 2, left-hand), multiplied by the number of devices.

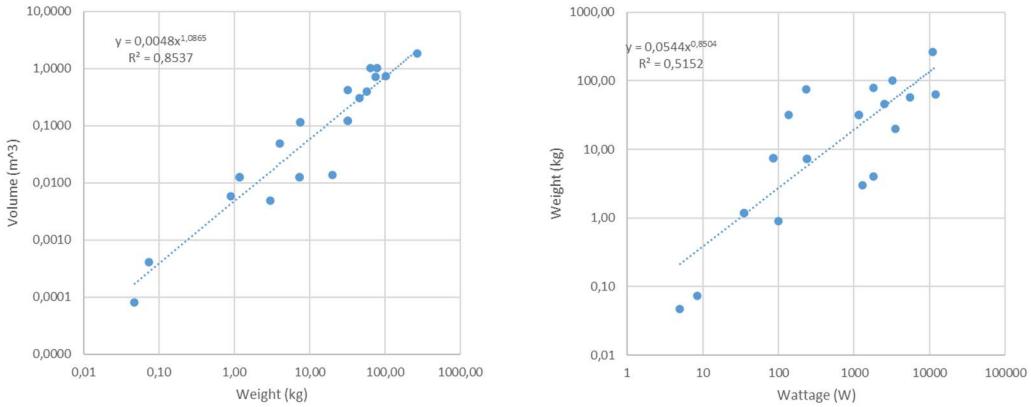

Figure S6. Correlation between weight (in kg) and Wattage (W) (right-hand graph), and between volume (m3) and weight (kg) (left-hand graph). Log-log scales.

Annual material requirements refer to the quantity of inputs that are necessary to produce the new devices that are going to replace the old ones arriving to the end of their lifetime. We estimate the annual flows by dividing the stock of devices by their lifetime, per type of appliance. Table S2 lists the assumptions considered for the lifetime of the appliances.

Table S2. Assumptions for the lifetime of consumer goods in 2020 and 2050, in years[8]

Sector	Category	Appliance	2020	2050	Source
Residentia	Lighting	Lamps	3	6	OSRAM, Richet et al., 2019
	Hygiene	Washing machine	13	15	Reale et al., 2019
		Water heater	17	17	Kemna et al., 2007
	Food preparation	Refrigerator	15	15	Reale et al., 2019
		Freezer	15	15	Reale et al., 2019
		(electric) Stove	13	13	HWA, 2020
		(electric) oven	13	13	HWA, 2020
	Communication & entertainment	Television	6	6	Reale et al., 2019
		Mobile phone	3	3	Bento, 2016
		PC (internet access)	5	5	Reale et al., 2019 (laptop)
	Thermal demand	Fan	10	10	BRE, 2009
		Portable air conditioner	15	15	Reale et al., 2019
	Miscellaneous	Small electric load devices: set-top	3	3	own assumption (electronics)
Commerci	Lighting	Lamps	3	6	OSRAM, Richet et al., 2019
	Hygiene	Washing machine	6	6	Bio Intelligence Service, 2011
		Water heater	13	13	IEA ETSAP, 2012
	Food preparation	Commercial refrigeration	10	10	JRC, 2014
		Industrial refrigeration	12	12	Climatetech, 2020
		(electric) Stove	15	15	Climatetech, 2020
	Communication & entertainment	Television	6	6	Reale et al., 2019
		PC (internet access)	5	5	Statistica, 2020
	Thermal demand	Fan	10	10	BRE, 2009
		Portable air conditioner	15	15	Reale et al., 2019
	Productive uses	Power in agriculture, fishery, etc.	13	15	own assumption (same as washing machines)
		Heating in agriculture, fishery, etc.	15	15	own assumption (same as portable ACs)

[8] OSRAM (2020), https://www.osram-group.com/en/sustainability/environmental/product-lifecycle-management/lca-incandescent

Appendix 4 lists the main inputs used in the material analysis. The shares of the main materials (steel, aluminum and plastics) come from the analysis of the bill of materials (BOM) of typical products that are provided by the manufacturers, following common practices in the literature (e.g., ADEME, 2019). The only exception is light bulbs for which we consider an "artificial" BOM that combines the material distribution of each one of the three main technologies in the market (conventional, CFL and Led). In addition, we calculate the embodied energy of the appliances, which includes the energy required for raw materials extraction and for manufacturing, while excluding transportation. For that we based on the estimates that are published in the literature (see sources in Appendix 4).

Therefore, the estimations for the number of devices, energy demand and materials consumption revise those in LED and serve as reference case or base (LEDbase) against which more aggressive scenarios will be compared.

To study the potential for reducing the energy demand and materials consumption from consumer goods, we formulate additional assumptions concerning the evolution of both demand and devices. This evolution should be influenced by three main trends: the widespread access to consumer goods and more generally to decent living standards for all particularly in the Global South; digital convergence with the emergence of multipurpose

Richter, J. L., Tähkämö, L., & Dalhammar, C. (2019). Trade-offs with longer lifetimes? The case of LED lamps considering product development and energy contexts. Journal of Cleaner Production, 226, 195-209.

Reale, F, Castellani, V, Hischier, R, Corrado, S, Sala, S,Consumer Footprint -Basket of Products indicator on Household appliances, EUR 29758 EN.

Kemna, R., Van Elburg, M., Li, W., & van Holsteijn, R. (2007). Eco-design of water heaters. Draft reports of tasks, 1-5.

HWA - Home Warranty of America (2020), https://www.hwahomewarranty.com/learning-center/homeowners/how-long-will-appliances-last

Bento, N. (2016). Calling for change? Innovation, diffusion, and the energy impacts of global mobile telephony. Energy Research & Social Science, 21, 84-100.

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Bio Intelligence Service (2011), Preparatory studies for Ecodesign Requirements of energy-using products: Lot 24: professional washing machines, dryers and dishwashers; Final Report, Part Dishwashers.

IEA ETSAP (2012). Cold Appliances. Energy Technology Systems Analysis Programme (ETSAP), IEA, January, www.etsap.org

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Statistica (2020), https://www.statista.com/statistics/267465/average-desktop-pc-lifespan/

devices such as the smartphone performing several tasks; and the sharing economy with the growth of new models of consumption based on the use, rather than ownership, of the device. These three trends have contrasting effects: decent living standards contribute to increase the demand for consumer goods, while digital convergence and sharing economies work to reduce the number of devices. We study the effects of these three trends through simulation analysis using an Excel spreadsheet. Next, we explain more in detail the estimation of the effect of each one of the three trends.

3.2. Decent living standards

At the level of decent living standards (DLS), we test the effect of different assumptions for the number and the diversity of appliances per person (or per household) that ensures basic material living conditions (Rao et al., 2019). DLS comprise a diverse set of essential items such as mobile phone, television, refrigerator, stove and electric lamp. A recent literature agrees around a minimum endowment of consumer goods that is necessary for an individual or a household to achieve DLS (e.g., Millward-Hopkins et al., 2020). Table S3 shows the assumptions considered in this study following this literature.

Table S3. Decent living standards assumptions

Category	Appliance	Service	Unit	2050 ownership per 100 HH	Source
Lighting	Lamps	2500	lumens/house	400	Millward-Hopkins et al., 2020
Hygiene	Washing machine	80	kg washing/year	100	Millward-Hopkins et al., 2020
	Water heater	20	liters/cap/day	100	Millward-Hopkins et al., 2020
Food preparation	Refrigerator	1	fridge-freezer (cooling)	100	Millward-Hopkins et al., 2020
	Electric Stove	1	stove (heat)	100	Hypothesis
	Electric oven	1	oven (heat)	100	Hypothesis
Communication	Television	1	TV (entertainment)	100	Rao & Ummel, 2017; Rao et al., 2019
	Mobile phone	1	phone person over 10 years old	300	Millward-Hopkins et al., 2020
	PC (internet access)	1	laptop (productive/ent./com.)	100	Millward-Hopkins et al., 2020
Thermal demand	Fan	15	m2/cap (cooling)	100	Millward-Hopkins et al., 2020
	Portable AC	15	m2/cap (cooling/heating)	100	Millward-Hopkins et al., 2020
Miscellaneous	Miscellaneous				

* can run on gas in 2020. Assumed a mean household size of 4 persons and a mean house size of 60m2.

Our approach consists of comparing the ownership of consumer goods in the base case with these minimum thresholds by region, particularly in the Global South. If the ownership is lower than the minimum threshold, we estimate the number of devices and the respective additional energy demand that would be necessary to ensure the access to decent living standards for all.

3.3. Digital convergence

Digital convergence can reduce both the number of devices and the energy intensity of the provision of the services (e.g., watching media in a mobile phone instead of a television). This is a new topic of research and the literature is extremely limited. We will use some recent works on the potential of digitalization of consumer innovations (e.g., Wilson et al., 2020).

We analyze the effects of digital convergence focusing on the electronic devices. This concerns mainly communication and entertainment goods and miscellaneous small plug-in loads. For the formers, we study the effect of the convergence of PCs/laptops, televisions and mobile phones into a single media device. This "super" device could provide portable communication and entertainment, as well as be used for productive uses (alone or connected to other devices). In the commercial sector, this corresponds to the widespread of single multimedia device such as all-in-one interactive TV systems already available in the medium to high-end range hotels. Finally, for small plug-in loads, we assume a reduction in the number of devices that would become redundant by the converging devices. We already observe a reduction in the number of some plug-loads which are substituted by services provided by applications ("apps") in smartphones (alarm clocks, radio set, VCR, etc.).

3.4. Sharing economies

We examine the potential for reducing energy and materials consumption by lowering the number of devices through their collective use. Sharing equipment lowers the energy and carbon footprint of households (Ivanova & Büchs, 2020; Ivanova et al., 2020). Sharing reduces the number of devices necessary to serve the same needs for lighting, entertainment, hygiene, etc. In addition, the devices can be used more intensively (higher load factor), more efficiently (at the lowest energy consumption and cost) or both.

We consider that one third of the population below 30 and above 65 years old co-live in shared houses, hosting in average 10 households, in 2050. This would assume the pursuit of the trend for co-living in these categories of age for several reasons (schooling, early-career needs, retirement, socializing, etc.) (CBRE, 2020).[9] Co-living reduce the number of appliances needed for lighting or food preparation such as lights, refrigerators, freezers, stoves and ovens (Ivanova & Büchs, 2020).

On the other hand, several devices are increasingly centralized at the level of buildings or at the level of the community. For example, washing machine rooms are not unusual in multifamily buildings in North America and are increasingly see in other parts of the world like in Europe, whereas laundry shops open almost everywhere. Another example is the increasing centralization of equipment such as Heating, Ventilating and Air Conditioning (HVAC) systems at the building level. Therefore we examine the possibility to reduce the number of appliances and equipment by centralizing washing machines, water heaters and portable air conditioners.

Table S4 summarizes the assumptions for digital convergence and sharing economies.

For the rest of the paper, we develop the following scenarios:

- LEDbase: 11-regional interpretation of the original LED (cf. Grubler et al., 2018, which updated the scenario GEA Efficiency for 2020, cf. Ürge-Vorsatz et al., 2012), energy use remains largely the same, number of devices changes due to the new categorization;
- LEDrev: revision of LEDbase explicitly considering impacts of assuring DSL for all (+), digital convergence (-), and sharing economy (-);
- LEDrev-LW: scenario sensitivity on LEDrev considering lightweighting of products (decrease in material intensity to a third of the levels in 2020);
- LEDrev-LW-LTX: scenario sensitivity on LEDrev-LW considering a 25% extension in the lifetime of every appliance.

[9] Guardian (2019), 'Co-living': the end of urban loneliness-or cynical corporate dormitories?', 3/9/2019.

Table S4. Assumptions for the calculation of the potential of digital convergence and sharing economies

Sector	Category	Appliance	Type	Sharing house-holds	Sharing level	Digital convergent devices per 100 Households	Energy intensity	Notes
Residential	Lighting	Lamps	sharing	10	age		double	(a)
	Hygiene	Washing machine	sharing	10-100	building, age, urbanization		double	(b)
		Water heater	sharing	10	age, building		double	(c)
	Food preparation	Refrigerator	sharing	10	age		double	(a)
		Freezer	sharing	10	age		double	(a)
		Electric stove	sharing	10	age		double	(a)
		Electric oven	sharing	10	age		double	(a)
	Thermal demand	Portable air conditioner	sharing	10	building		double	(d)
	Communication	Television	digital conv.			0	unchanged	(e)
		Mobile phone	digital conv.			100	unchanged	(f)
		PC (internet access)	digital conv.			0	unchanged	(e)
	Miscellaneous	Misc.electric loads	digital conv.			33	unchanged	(g)
Commercial	Hygiene	Water heater	sharing	10	building		unchanged	(h)
	Thermal demand	Portable air conditioner	sharing	10	building		unchanged	(h)
	Communication	Television	digital conv.			0	unchanged	(e)
		PC (internet access)	digital conv.			100	unchanged	(i)

(a) A third of the population under 30 years and over 65 years share houses with 10 households in average.
(b) Half of the urban population served by laundry shops (1 machine per 100 households); people living in multifamily buildings in urban areas and co-living (elderly, young, etc.) share laundry room (1 machine per 10 households).
(c) Shared in co-living houses (elderly, young, etc.) and at the building level in average by 10 households.
(d) Shared at building level.
(e) Converge into an “all-in-one” media portable device.
(f) One per capita. Standby energy reduction compensates for increase in energy intensity (kWh/year).
(g) Digital convergence divides by three the number of electric loads.
(h) Shared at commercial building level.
(i) Become “all-in-one” media converging device. Efficiency improvements and standby consumption reduction compensate the effect of high load factor.

4. IMPACT ON THE NUMBER OF DEVICES

We estimate the growth in the demand for consumer goods from 2020 to 2050 by comparing the growth in the base scenario (LEDbase) with the increase in the number of devices assuming the adoption of decent living standards, digital convergence and sharing economies (LEDrev). Figure S7 shows the results for the decomposition analysis at the global level.

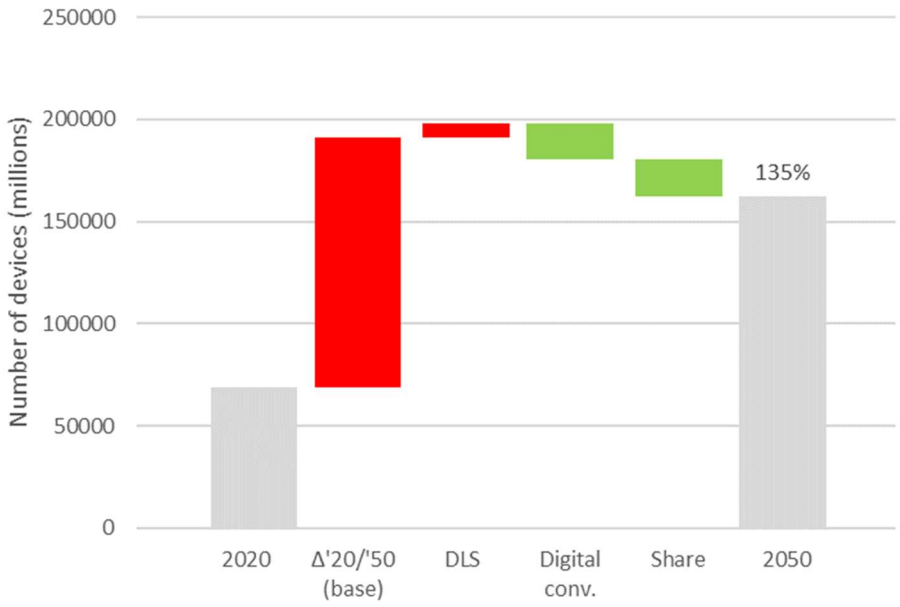

Figure S7. Disaggregation of the growth in the number of appliances in 2050 in terms of the effect of growth in the base scenario (LEDbase), decent living standards (DLS), digital convergence and sharing economies (2050=LEDrev).

The number of devices in 2020 has been revised downwards due to a more detailed analysis of a larger number of appliances, using the most recent data. We estimate the global stock of consumer goods at around 69 billion units, instead of the 105 billion assumed in LED for the base year.

In 2020, the 69 billion units provided a wide range of services that are calculated in Appendix 3. In the residential sector, for example, mobile phones supported thousands of billions of hours of talk, web browsing or video watching. Similarly, washing machines handled almost a million tons of laundry washed, while refrigerators and freezers refrigerated half of a billion cooling liters.

In the base scenario (LEDbase), the number of consumer goods increases 177% to reach 191 billion units in 2050. This growth is mainly explained by the increase in demand from the Global South (+107 billion units) that is driven by the increase in the revenue per capita

(Table S5). The expected rise in revenue also explains the relative modest additional growth of devices (+7 billion) that would be needed to ensure decent living standards for all. Digital convergence more than compensates that growth, contributing to decrease the number of devices in 18 billion. Finally, sharing devices would further cut the need of 18 billion devices. Taken together, in the LEDrev scenario, digital convergence and sharing would limit the increase in the number of devices to 162 billion units (+135% or less 42 percentage points than the growth in LEDbase).

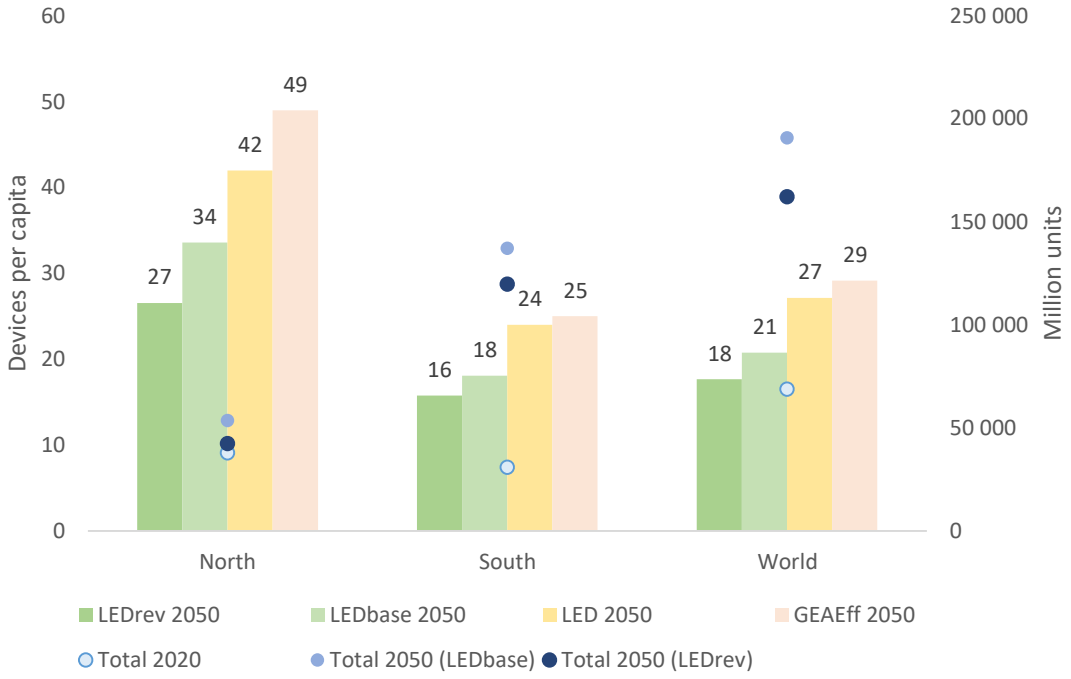

Figure S8. Comparing the number of devices (total and per capita) in 2050 in LEDbase and LEDrev with previous studies (LED and GEA Efficiency).

Figure S8 compares the projections for the number of devices in 2050 in previous studies. LEDbase is already much lower than LED which estimated the number of appliances at 252 billion units in 2050 (light blue dots). This is mainly due to a more granular treatment of the number of appliances in the commercial sector (-26 billion units). In addition, by analyzing explicitly a largest set of technologies, we were able to improve the estimation of the residual category “Others” (-41 billion units).

Therefore, the number of devices per capita reduces to 34 in LEDbase, or to 27 per capita when taking into account DLS, digital convergence and sharing, in LEDrev.

Table S5. Increase in the number of devices from 2020 to 2050, by region. (LEDbase at top and LEDrev at bottom)

(LEDbase)

Sector	Category	Appliance	2020	WEU	NAM	PAO	EEU	FSU	SAS	CPA	PAS	LAM	SSA	MEA	2050
Residential	Lighting	Lamps	27631	2477	755	411	500	3014	8358	18091	8254	7391	1432	6883	85194
	Hygiene	Washing machine	1058	30	82	3	4	52	491	253	105	133	195	152	2559
		Water heater	1029	42	71	7	5	56	475	285	117	139	207	180	2613
	Food preparation	Refrigerator	1258	40	76	6	5	47	528	299	104	125	210	151	2849
		Freezer	430	14	98	3	-15	20	140	235	79	79	33	38	1153
		(electric) Stove	549	66	159	18	18	67	200	282	131	144	-11	118	1741
		(electric) oven	185	38	47	11	7	15	71	105	33	36	29	32	607
	Communication & enti	Television	1392	95	170	22	9	29	302	380	177	70	178	123	2946
		Mobile phone	6167	22	55	20	20	-33	376	123	121	90	635	136	7732
		PC (internet access)	1211	216	416	56	65	139	487	1071	343	308	108	256	4675
	Thermal demand	Fan	1239	55	171	14	35	74	130	200	48	164	120	159	2409
		Portable air conditioner	117	21	22	2	3	11	29	39	10	18	13	19	302
	Miscellaneous	Miscellaneous electric loads	3230	440	99	24	48	251	1042	1726	686	691	322	640	9198
Commercial	Lighting	Lamps	18258	-91	990	62	193	1787	6118	10353	5624	5169	235	5296	53994
	Hygiene	Washing machine	53	1	4	0	0	3	25	13	5	7	10	8	128
		Water heater	842	99	129	27	18	44	231	330	99	110	95	100	2125
	Food preparation	Commercial refrigeration	45	6	8	2	1	3	13	20	6	7	6	6	121
		Industrial refrigeration	4	0	1	0	0	0	1	1	0	0	0	0	9
		(electric) Stove	410	69	86	19	12	28	138	203	62	68	56	61	1214
	Communication & enti	Television	1392	95	170	22	9	29	302	380	177	70	178	123	2946
		PC (internet access)	1163	148	349	37	52	154	438	839	269	168	70	251	3936
	Thermal demand	Fan	1239	55	171	14	35	74	130	200	48	164	120	159	2409
		Portable air conditioner	29	4	3	0	0	2	5	6	1	3	2	4	60
	Productive uses	Power in agriculture, fishery,	59	7	9	2	1	3	16	24	8	7	6	7	149
		Heating in agriculture, fishery	13	1	1	0	0	1	1	1	0	1	1	1	20
		TOTAL	69003	3948	4143	780	1025	5869	20044	35457	16507	15165	4247	14902	191092
		Population (millions)	7776	559	453	151	116	277	2373	1408	693	741	1694	704	9169
		units per capita	9	7	9	5	9	21	8	25	24	20	3	21	21

(LEDrev)

Sector	Category	Appliance	2020	WEU	NAM	PAO	EEU	FSU	SAS	CPA	PAS	LAM	SSA	MEA	2050
Residential	Lighting	Lamps	27631	1061	-365	19	213	2408	6916	14922	6935	5982	1001	5720	72444
	Hygiene	Washing machine	1058	-130	-69	-41	-27	-14	207	-111	-49	53	268	2	1149
		Water heater	1029	-40	-9	-15	-9	24	408	134	55	127	377	116	2196
	Food preparation	Refrigerator	1258	1	41	-5	-2	32	442	217	69	143	314	116	2627
		Freezer	430	-7	75	-3	-19	13	115	197	66	65	21	25	979
		(electric) Stove	549	31	119	7	12	57	531	255	145	289	358	164	2516
		(electric) oven	185	27	34	7	5	12	535	415	152	289	415	165	2242
	Communication & enti	Television	1392	-199	-147	-62	-42	-78	-166	-241	-54	-103	59	-87	271
		Mobile phone	6167	22	55	20	20	-33	376	300	121	390	635	136	8210
		PC (internet access)	1211	-380	-279	-118	-32	-52	-27	-104	-33	-81	282	-60	325
	Thermal demand	Fan	1239	55	171	14	35	74	317	200	48	277	373	172	2975
		Portable air conditioner	117	9	7	-2	1	7	540	420	154	295	419	174	2141
	Miscellaneous	Miscellaneous electric loads	3230	-188	-416	-146	-78	-28	186	206	86	67	22	125	3066
Commercial	Lighting	Lamps	18258	-91	990	62	193	1787	6118	10353	5624	5169	235	5296	53994
	Hygiene	Washing machine	53	1	4	0	0	3	25	13	5	7	10	8	128
		Water heater	842	-120	-119	-37	-18	-30	-42	-115	-54	-49	-14	-32	213
	Food preparation	Commercial refrigeration	45	6	8	2	1	3	13	20	6	7	6	6	121
		Industrial refrigeration	4	0	1	0	0	0	1	1	0	0	0	0	9
		(electric) Stove	410	69	86	19	12	28	138	203	62	68	56	61	1214
	Communication & enti	Television	1392	95	170	22	9	29	302	380	177	70	178	123	2946
		PC (internet access)	1163	-354	-236	-110	-30	-7	-16	-150	-48	-160	-37	-16	0
	Thermal demand	Fan	1239	55	171	14	35	74	130	200	48	164	120	159	2409
		Portable air conditioner	29	-3	-4	-2	-1	0	-3	-7	-3	-1	-1	0	6
	Productive uses	Power in agriculture, fishery,	59	7	9	2	1	3	16	24	8	7	6	7	149
		Heating in agriculture, fishery	13	1	1	0	0	1	1	1	0	1	1	1	20
		TOTAL	69003	-73	300	-353	282	4312	17065	27731	13521	13078	5104	12381	162353
		Population (millions)	7776	559	453	151	116	277	2373	1408	693	741	1694	704	9169
		units per capita	9	0	1	-2	2	16	7	20	20	18	3	18	18

5. IMPACT ON ENERGY DEMAND

Figure S9 presents the increase in the energy demand from 2020 to 2050. Similarly to Figure S7, we show separately the effects of decent living standards, digital convergence and sharing economies that lowers the energy demand from the scenario LEDbase to LEDrev.

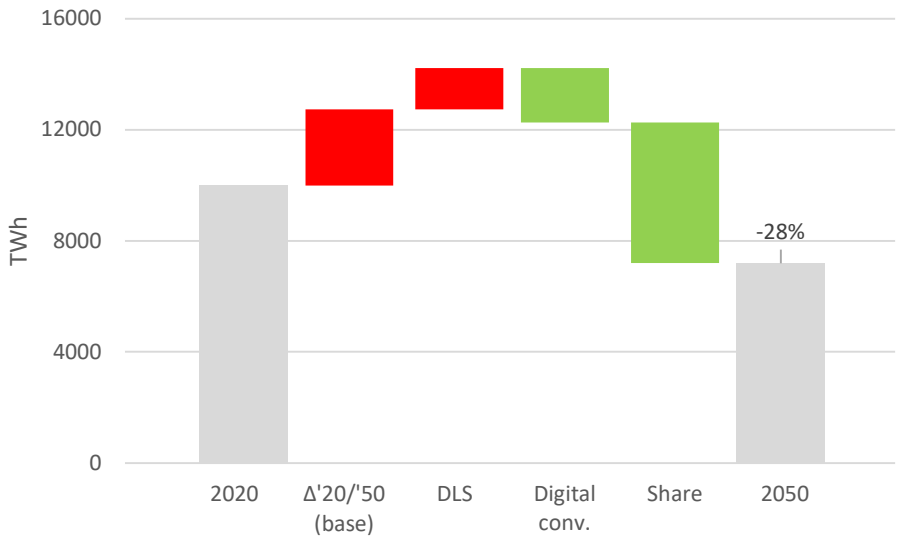

Figure S9. Disaggregation of the growth in the energy demand from consumer goods in 2050 in terms of the increase in the base scenario (LEDbase), decent living standards (DLS), digital convergence and sharing economies (2050=LEDrev).

From right to left, energy demand in LEDbase increases 28% (+2,752 TWh) despite the growth in the number of devices of 177% in 2050. This is due to the trends in energy efficiency which are assumed to be the same as in LED. Ensuring decent living standards increases energy demand by around 1,500 TWh. This would be more than compensated by digital convergence (- 1,952 TWh). Finally, sharing appliances decreases the energy consumption around 5,000 TWh. As a result, the total energy demand in LEDrev falls to 7,194 TWh, 28% below the 2020 levels.

Comparing to LED, energy use changes slightly in 2050 in LEDbase (12,738 TWh instead of 11,477 TWh in LED). Again this results from the more explicit treatment of the consumer goods that were previously considered in the residual category “others”, along with a more detailed analysis of the consumption from appliances in the commercial sector. Energy demand is much lower (7,111 TWh) in the LEDrev scenario.

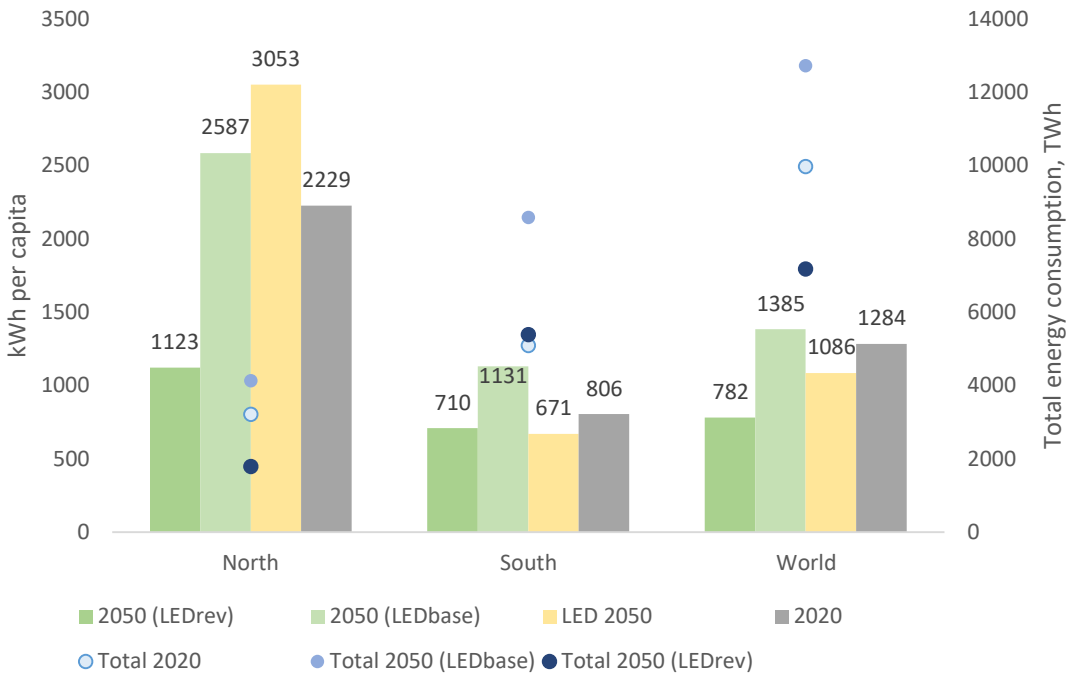

Figure S10. Comparing the energy demand from consumer goods (total and per capita) in LEDbase, LEDrev and LED, by region.

Figure S10 compares the energy consumption, total and per capita, in different scenarios. LEDrev significantly reduces the energy use from appliances, particularly in the Global North where consumption shrinks to a third in comparison to the original LED scenario. Table S6 shows the changes in energy use from 2020 to 2050 under LEDrev, by region and by appliance. Energy use mainly decreases by centralizing equipment as water heaters at the building level, and converging electronics such as PCs, TVs or other peripherals into a smaller number of highly efficient portable devices and all-in-one media stations.

Table S6. Increase in the energy demand from consumer goods from 2020 to 2050 in LEDrev (TWh)

Energy demand TWh (LEDrev)

Sector	Category	Appliance	2020	WEU	NAM	PAO	EEU	FSU	SAS	CPA	PAS	LAM	SSA	MEA	2050
Residential	Lighting	Lamps	356	-9	-10	-3	-2	-5	-13	-27	-11	-12	-4	-10	612
	Hygiene	Washing machine	166	-11	-17	-4	-3	-8	-8	-2	-5	-6	4	-9	59
		Water heater	818	-25	-40	-11	-7	-16	-15	-34	-14	-3	39	-15	586
	Food preparation	Refrigerator	219	-5	-6	-2	-1	-2	-11	-10	-4	2	11	-4	330
		Freezer	150	-6	-8	-2	-1	-1	-6	-10	-3	-4	-3	-3	260
		(electric) Stove	75	-2	-2	-1	0	-1	16	-1	1	7	18	2	122
		(electric) oven	21	0	0	0	0	0	19	13	5	10	16	5	91
	Communication & enti	Television	400	-34	-36	-10	-6	-12	-79	-104	-39	-29	-20	-35	46
		Mobile phone	11	0	0	0	0	0	0	0	0	1	0	0	15
		PC (internet access)	112	-40	-46	-12	-6	-13	-45	-103	-33	-34	15	-28	28
	Thermal demand	Fan	86	0	0	0	0	0	6	0	0	4	8	0	85
		Portable air conditioner	203	-20	-29	-2	-3	-6	305	227	86	165	242	92	1349
	Miscellaneous	Miscellaneous electric loads	364	-57	-47	-16	-8	-19	-69	-123	-48	-48	-24	-41	250
Commercial	Lighting	Lamps	695	0	0	0	0	0	0	0	0	0	0	0	937
	Hygiene	Washing machine	53	0	0	0	0	0	0	0	0	0	0	0	79
		Water heater	3877	-505	-571	-147	-84	-171	-626	-1024	-350	-364	-251	-305	489
	Food preparation	Commercial refrigeration	83	0	0	0	0	0	0	0	0	0	0	0	172
		Industrial refrigeration	513	0	0	0	0	0	0	0	0	0	0	0	1009
		(electric) Stove	112	0	0	0	0	0	0	0	0	0	0	0	118
	Communication & enti	Television	400	0	0	0	0	0	0	0	0	0	0	0	450
		PC (internet access)	216	-67	-78	-19	-11	-21	-79	-173	-56	-57	-19	-47	0
	Thermal demand	Fan	86	0	0	0	0	0	0	0	0	0	0	0	66
		Portable air conditioner	51	-11	-14	-1	-2	-4	-5	-8	-3	-3	-2	-2	6
	Productive uses	Power in agriculture, fishery,	828	0	0	0	0	0	0	0	0	0	0	0	29
		Heating in agriculture, fishery	19	0	0	0	0	0	0	0	0	0	0	0	0
	Stand by	(all)	76	-15	-12	-5	-2	-3	-6	-13	-5	-7	-2	-3	2
		TOTAL	9987	-807	-918	-235	-138	-281	-616	-1394	-479	-378	29	-402	7192
		Population (millions)	7776	559	453	151	116	277	2373	1408	693	741	1694	704	9169
		kWh per capita	1284												784

6. IMPACT ON MATERIAL CONSUMPTION

The demand for consumer goods that is expected in 2050 have important repercussions in material consumption. The most significant impacts of LEDbase and LEDrev are precisely in lowering these material requirements. Figure S11 shows the changes in material consumption in terms of volume (left-hand) and weight (right-hand).

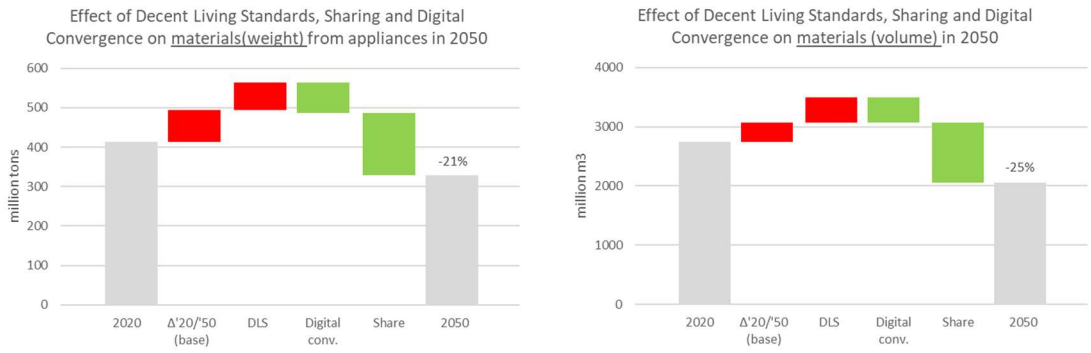

Figure S11. Disaggregation of the material requirements (weight and volume) from consumer goods in 2050 in terms of the effect of growth in the base scenario (LEDbase), decent living standards (DLS), digital convergence and sharing economies (2050=LEDrev).

The material requirements in weight lowers 21% in LEDrev, despite the increase of 135% in the number of appliances in 2050 that is projected in this scenario. Digital convergence (-78 million tons) alone absorbs the growth expected in LEDbase (+80 million tons). Additionally, the material savings from sharing devices would amount to 157 million tons. This is even higher than the projected increase in material consumption in base (LEDbase) and in DLS altogether.

On the other hand, the materials volume lowers 25% assuming the continuation of the observed trends in the relation between size and weight, including downsizing in several objects such as miniaturization in electronics.

Table S7 shows the effect of the estimated demands of consumer goods in 2050 in the consumption of materials (both stock and annual fluxes) by region, comparing to 2020. As for the stock of appliances, most of the reduction in the material requirements come from the Global North where they reduce to almost a third under LEDrev. Material needs per capita lowers in the North to 46 kg in 2050 from 133 kg in 2020.

The annual replacement fluxes, on the other hand, refer to the material consumption needed to produce the consumer goods which substitute those arriving to the end of lifetime. Under

the LEDrev scenario, the annual replacement flux reduces from 49 million tons to 33 million tons between 2020 and 2050. Most of the reductions occur in the Global North where the annual flux shrinks to less than a third thanks to digital convergence and sharing, while it remains stable in the Global South in 2050. Therefore material needs lowers to 4 kg per capita in the Global North, comparing to 17 kg per capita in 2020.

Table S7. Material requirements in 2020 and 2050 (LEDbase and LEDrev), by region

	2020			2050 LEDbase			2050 LEDrev		
	Volume (million m3)	Weight (million tons)	kg per capita	Volume (million m3)	Weight (million tons)	kg per capita	Volume (million m3)	Weight (million tons)	kg per capita
Stocks									
World	**2741**	**414**	**53**	**3064**	**494**	**54**	**2144**	**342**	**37**
North	1265	192	133	864	140	87	455	73	46
South	1476	222	35	2200	355	47	1689	270	36
Annual flux									
World	**312**	**49**	**6**	**354**	**59**	**8**	**199**	**33**	**4**
North	151	24	17	100	17	12	45	7	4
South	161	25	4	254	43	7	154	25	3

Table S8 presents the changes in the demand of specific materials for annual replacement of consumer goods under different scenarios. The annual demand of steel, aluminum and plastics in LEDrev reduces to a third in average, despite the double of devices expected for 2050. In comparison, the demand of steel, aluminum and plastics grows 17%, 29% and 23% respectively in the LEDbase scenario, highlighting the importance of digital convergence and sharing to reduce material consumption. A large part of the material savings come from the regions in the Global North (Table S9).

We estimate the embodied energy, i.e. the energy necessary for the raw materials extraction and the manufacturing of the appliances.[10] We calculate the embodied energy by appliance based on the needs for typical models in 2020. Product changes may alter the embodied energy of the appliances in 2050; however the energy intensity may remain similar in 2050 due

[10] We follow a methodology close to:

-Boustani, A., Sahni, S., Graves, S. C., & Gutowski, T. G. (2010, May). Appliance remanufacturing and life cycle energy and economic savings. In *Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology* (pp. 1-6). IEEE;

-and Ciceri, N. D., Gutowski, T. G., & Garetti, M. (2010, May). A tool to estimate materials and manufacturing energy for a product. In Proceedings of the 2010 IEEE international symposium on sustainable systems and technology (pp. 1-6).

to the even more sophisticated methods of production and the trend for digitalization of the devices, with increasing shares of electronics (highly energy intensive). In this context, embodied energy reduces almost 40% in 2050 under the LEDrev scenario, comparing to an increase of 22% in LEDbase. This result stresses again the potential for material savings that can be reached with digital convergence and sharing of devices.

Table S8. Annual replacement flux in 2020 and 2050, by type of material (million tons unless specified otherwise)

	2020	2050 LEDbase	Δ% to 2020	2050 LEDrev	Δ% to 2020
Total weight	**49**	**59**	**21%**	**33**	**-34%**
Steel	23	27	17%	16	-30%
Aluminum	2	3	29%	2	-36%
Plastic	11	13	23%	8	-24%
Embodied (TJ)	**4459**	**5445**	**22%**	**2784**	**-38%**

Table S9. Comparing the annual material flows (in million tons) associated to the replacement of old consumer goods in 2020 and 2050 under LEDrev, by region

Materials million tons (LEDrev)

Sector	Category	Appliance	2020	WEU	NAM	PAO	EEU	FSU	SAS	CPA	PAS	LAM	SSA	MEA	2050
Residential	Lighting	Lamps	1	-0,11	-0,12	-0,04	-0,02	-0,01	0,01	0,02	0,03	0,00	-0,01	0,02	0
	Hygiene	Washing machine	4	-0,62	-0,37	-0,19	-0,12	-0,11	0,24	-0,75	-0,32	-0,13	0,33	-0,12	2
		Water heater	3	-0,40	-0,27	-0,13	-0,08	-0,04	0,60	-0,23	-0,10	0,04	0,62	0,14	4
	Food preparation	Refrigerator	7	-0,54	-0,28	-0,18	-0,12	-0,07	0,96	-0,16	-0,19	0,02	0,63	0,09	7
		Freezer	1	-0,13	0,03	-0,04	-0,06	-0,01	0,09	0,17	0,05	0,05	-0,02	-0,02	1
		(electric) Stove	0	-0,01	0,00	0,00	0,00	0,01	0,06	0,01	0,02	0,03	0,03	0,02	0
		(electric) oven	0	0,00	0,00	0,00	0,00	0,00	0,08	0,06	0,02	0,04	0,06	0,02	0
	Communication & enti	Television	2	-0,25	-0,18	-0,08	-0,05	-0,10	-0,24	-0,30	-0,07	-0,18	-0,04	-0,11	0
		Mobile phone	0	0,00	0,00	0,00	0,00	0,00	0,02	0,02	0,01	0,03	0,04	0,01	1
		PC (internet access)	2	-0,56	-0,41	-0,17	-0,05	-0,08	-0,06	-0,15	-0,05	-0,12	0,15	-0,09	0
	Thermal demand	Fan	0	0,01	0,03	0,00	0,00	0,01	0,00	-0,01	-0,01	0,01	0,01	0,01	0
		Portable air conditioner	0	0,03	0,03	-0,02	0,00	0,02	0,69	0,50	0,18	0,38	0,55	0,23	3
	Miscellaneous	Miscellaneous electric loads	17	-1,80	-2,82	-0,98	-0,56	-0,51	-0,17	-0,94	-0,34	-0,48	-0,28	-0,03	8
Commercial	Lighting	Lamps	0	-0,10	-0,05	-0,02	-0,01	0,00	0,02	0,01	0,02	0,01	-0,01	0,02	0
	Hygiene	Washing machine	2	-0,19	-0,05	-0,06	-0,04	0,01	0,50	-0,03	-0,01	0,03	0,18	0,10	3
		Water heater	4	-0,65	-0,65	-0,20	-0,10	-0,17	-0,28	-0,68	-0,30	-0,28	-0,10	-0,20	1
	Food preparation	Commercial refrigeration	0	-0,01	0,00	0,00	0,00	0,00	0,03	0,04	0,01	0,01	0,01	0,01	0
		Industrial refrigeration	0	0,01	0,00	0,00	0,00	0,00	0,01	0,02	0,01	0,01	0,00	0,00	0
		(electric) Stove	1	0,00	0,01	0,00	0,00	0,01	0,07	0,08	0,02	0,02	0,03	0,02	1
	Communication & enti	Television	2	-0,14	-0,07	-0,05	-0,03	-0,06	0,00	0,02	0,05	-0,09	0,02	0,00	1
		PC (internet access)	2	-0,52	-0,35	-0,16	-0,04	-0,01	-0,02	-0,22	-0,07	-0,23	-0,05	-0,02	0
	Thermal demand	Fan	0	0,01	0,03	0,00	0,00	0,01	-0,01	-0,01	-0,01	0,01	0,00	0,01	0
		Portable air conditioner	0	-0,01	-0,01	-0,01	0,00	0,00	-0,01	-0,02	-0,01	-0,01	0,00	0,00	0
	Productive uses	Power in agriculture, fishery,	1	-0,11	-0,10	-0,03	-0,02	-0,03	-0,05	-0,11	-0,05	-0,05	-0,02	-0,03	0
		Heating in agriculture, fishery	0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0
		TOTAL	49	-6	-6	-2	-1	-1	3	-3	-1	-1	2	0	33
		Population (millions)	7776	559	453	151	116	277	2373	1408	693	741	1694	704	9169
		kg per capita	6												4

7. ALTERNATIVE SCENARIOS TO REDUCE MATERIAL FLOWS

We consider two sensitive scenarios regarding LEDrev. The first refers to an accelerated trend of reduction in the weight of appliances. The second sensitive scenario assesses the impact on annual material flows of a 25% extension of the appliances' lifetime.

7.1. Lightweight: accelerated reduction of appliances weight

We perform a sensitivity scenario assuming a higher reduction in the material requirements of the appliances than in LEDrev. More precisely, we assess the effect of the reduction to a third the average material weight of the appliances in 2050. This is around a third less than in LEDrev, following the expected reduction in the wattage of the devices to improve their energy efficiency.

Figure S12 shows the annual material flux in the lightweight sensitivity scenario (LEDrev-LW) and in the other scenarios. It is worthwhile to remember that the lightweight scenario is estimated on top of LEDrev, assuming the same increase in the number of appliances in 2050 (+135%), but only changing the material intensity (kg per unit) of the devices. Comparing to LEDrev, the accelerated reduction of unit weight in LEDrev-LW significantly lowers the total weight of appliances relatively to 2020 in -53%, instead of -34%. The highest reductions occur in the consumption of aluminum (-56%) in relative terms, and of steel (less 11 million tons) in absolute terms. These numbers are significantly lower than in LEDbase which projects an increase in the consumption of the materials under analysis.

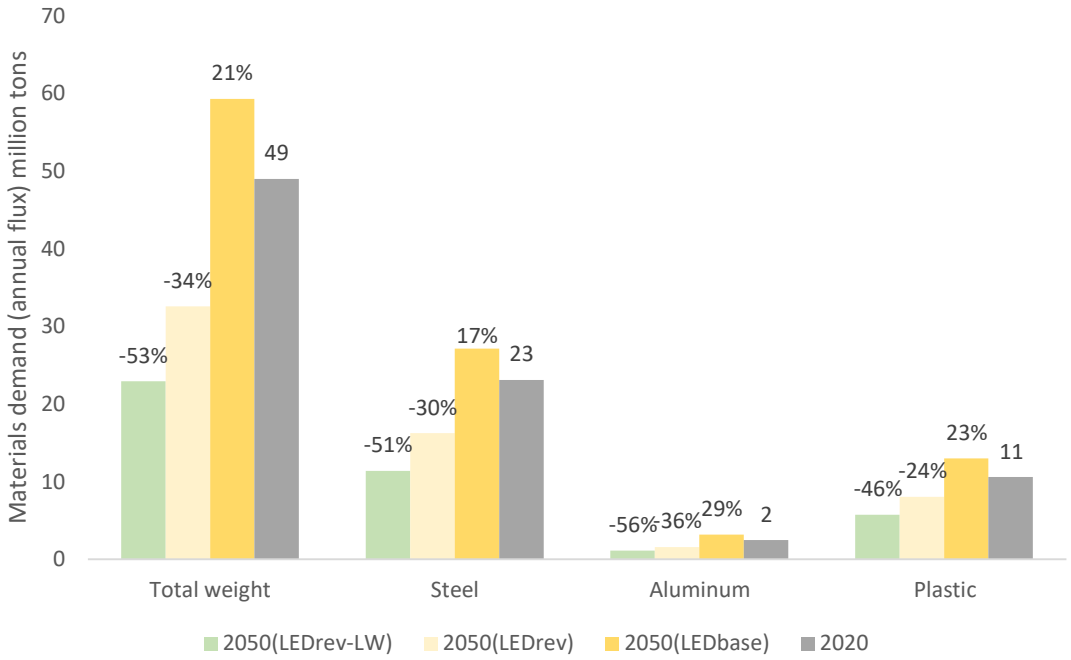

Figure S12. Comparing the annual material flux in 2020 with 2050 in LEDbase, LEDrev and LEDrev with a lightweight scenario (LEDrev-LW)

7.2. Lifetime extension

The second sensitivity analysis examines the effect of assuming a 25% extension of the lifetime of the appliances in the annual material fluxes. Lifetime extension should be less technically demanding comparing to lightweight which would require the introduction of new product architectures, production methods, and new materials that are even lighter than in LEDrev with similar robustness.

Extending the lifetime of the products entails a change in the marketing strategy of companies. These should move away from the well documented practices of programmed obsolescence, consisting of product design, manufacturing and marketing that artificially limit their useful live to accelerate the rates of replacement. Already in 1960, Vance Packard denounced some marketing strategies followed by companies to provoke artificial obsolescence through constant modernization of the models, lowering quality or fashion (Packard & McKibben, 1963). Nowadays there are laws in several countries (e.g. France) that prevent programmed obsolescence, but their enforcement remains complex.

The analysis shows that lifetime extension has an effect similar to lightweight in reducing the annual material demand (Figure S13). Enlarging the useful life of appliances in 25% — e.g. 20 years instead of 15 for the assumed lifetime of washing machines in 2050, scenario LEDrev-LTX—further reduces the total weight of consumer goods to -47% from -34% in LEDrev. The difference is relatively larger in plastics (-39% from -24% in LEDrev). Lifetime extension halves aluminum consumption comparing to current levels, and reduces the needs in steel in 5 million tons annually.

Considering the lifetime extension on top of the lightweight assumption, the scenario LEDrev-LW-LTX, reduces even further the material consumption of appliances. The consumption of steel, aluminum or plastics is almost cut by a half comparing to LEDrev. These results show the importance of considering the two measures, lifetime extension and material intensity reduction (lightweight), together to accelerate dematerialization in consumer goods.

These estimations assume that the share of the materials in the manufacturing of the devices remains the same in 2050. However, lifetime extension may have implications in the choice of the materials used in device manufacturing, as well as in the share of these materials. We recognize this limitation but considering the high levels of uncertainty about the manufacturing of products in 2050, it is more transparent to assume that the relative share of materials in production would not significantly change in the future. Therefore our estimations should be considered under that assumption.

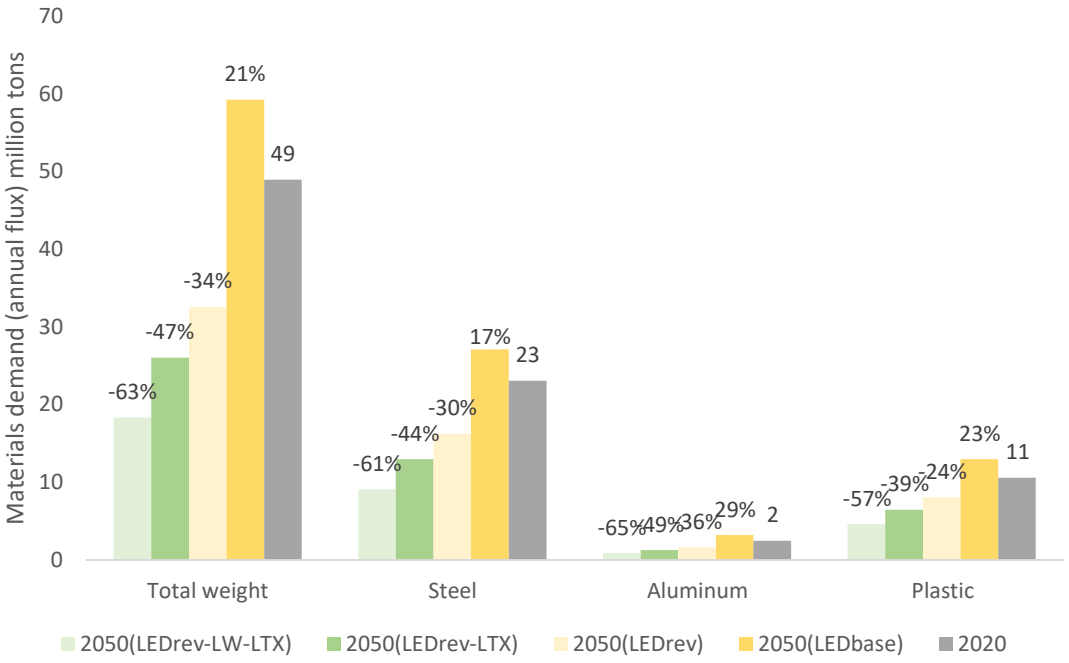

Figure S13. Comparing the annual material flux in 2020 with 2050 in LEDbase, LEDrev and LEDrev with a lifetime extension scenario (LEDrev-LTX) and the latter on top of the scenario assuming lightweight (LEDrev-LW-LTX)

8. CONCLUSION

In the face of a rapid growth in the demand of consumer goods that increases the pressure in materials consumption and puts at risk the efforts of decarbonization, strategies are needed to lower the environmental footprint of appliances in a way that achieves the 1.5ºC target in 2050 and enables access to modern services provided by consumer goods to the population in the Global South. The publication of the LED study in 2018 already advanced in the understanding of the effects of the rising demand for consumer goods and of the measures that could make it compatible with the needs of sustainable development.

Meanwhile the trends in the energy demand from appliances have accelerated (IEA, 2020ab), along with the signs of climate deregulation that brought the UN secretary general to urge the countries to declare a state of climate emergency. The pandemic did not put away the perception of the climate urgency, but rather accelerated some of the observed trends towards digitalization and the development of social innovations and new forms of organization of service provision (teleworking, online media, etc.) (Kikstra et al., 2021).

Therefore, there is the need for a finer-grain analysis, both spatially and by more type of products, to better understand the factors that drive the growth of energy demand and material consumption in appliances in order to design strategies to reduce them in line with the needs of decarbonization.

This study addresses this need by developing a more disaggregated analysis of the demand for consumer goods, now and in 2050, considering explicitly 11 regions instead of 2 in LED, and a larger range of consumer goods, including in the commercial sector. Additionally, this research aims to understand the potential of digital convergence and sharing for the decarbonization and the dematerialization of consumer goods.

We have re-estimated the previous LED scenario with the most up-to-date information on appliances demand and efficiency. This LEDbase scenario was then compared to a revised scenario (LEDrev) which includes the needs for ensuring decent living standards for all, as well as the savings enabled by digital convergence and sharing.

Table S10 shows the main results from the key scenario (LEDrev). The main outcomes are summarized as following:

- between 2020 and 2050, the number of appliances more than double in LEDrev while the population increases 18% in the same period, hence doubling the number of devices per capita (mainly in the Global South);

- energy demand reduces around a third in the same period, benefiting from efficiency improvements that reduces the energy intensity of the devices to a third of the levels in 2020;
- the material consumption lowers 20% thanks to the division by three of the material intensity of the devices.

Table S10. Decomposition analysis: Base case (LEDbase) with decent living standards, digital convergence and sharing (LEDrev)

	(1)	(2)	(3)	(4)			
	Number of appliances	**Energy demand**	**Material consumption**	**Population**	**Devices per cap**	**Energy intensity**	**Material intensity**
	(millions)	(TWh)	(million kg)	(millions)	(1)/(4)	(2)/(4)	(3)/(4)
2020	69,003	9,987	414	7,776	8.9	0.145	0.006
2050	162,353	7,192	342	9,169	17.7	0.044	0.002
cagr	2.9%	-1.1%	-0.6%	0.6%	2.3%	-3.9%	-3.4%
2050/2020	**2.35**	**0.72**	**0.83**	**1.18**	**2.00**	**0.31**	**0.35**

A more in-depth analysis of the energy intensity distinguishes the effect of the change in the weights of the categories of appliances (structural effect) from the improvement of intensity within the categories.

Structural change amplifies the effects of efficiency improvement. By reducing the weight of large, more energy intensive, devices, digital convergence and sharing contributes to lower the overall energy demand from appliances (Figure S14). The structural effect alone reduces 40% (the reverse of the multiplier 1.89) the energy demand, comparing with the hypothetical situation under which the basket of consumer goods remains unchanged between 2020 and 2050. Accounting for the structural effect is important as, in the extreme case, it could explain the paradox under which the overall energy demand from consumer goods would reduce even if the consumption within a large number of categories increases (namely due to the democratization of their use). The structural effect also explains the feasibility of deep reductions in energy demand (and thus carbon emissions) without assuming unprecedent rates of efficiency improvement.

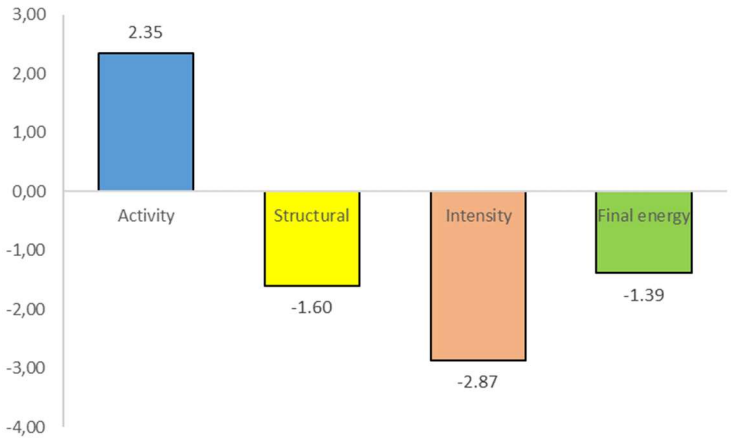

Figure S14. Disaggregation analysis: 2020-2050 multiplier/divisor. Changes in 2020–2050 in total global activity, structure of goods, energy intensity and final energy demand. Multiplier or divisor depending on the number being positive or negative.

Table S11 compares the outcomes of the different scenarios. These are the main highlights:

- comparing to the previous LED study, the number of devices estimated for 2020 are much lower, particularly in the Global South;
- LEDrev projects a lower number of devices in 2050, and a much lower energy use in 2050, due to a more detailed analysis by category of appliances;
- the difference between the estimations in LEDrev and LEDbase (which updates LED with new information and a finer-grain disaggregation by region and by appliances) roughly corresponds to the potential of digital convergence and sharing to lower carbon emissions from appliances: these two processes can more than compensate the increase in the number of devices due to ensuring decent living standards for all; while still lowering the number of devices in 2050 from 191 billion units to around 160 billion, reducing 44% the energy demand to 7,192 TWh and halving the material weight for annual replacement from 59 tons to 33 tons;
- the cost of the 30 million units saved through digital convergence and sharing in LEDrev correspond to 9 trillion US dollars at the current prices (using the price in global outlets, e.g. Amazon, of representative items of each category).

Table S11. Comparison of scenarios

	2020 LED	2050 LED	2020 LEDbase	2050 LEDbase	2050 LEDrev
Million units					
World	105,034	252,751	69,003	191,092	162,353
North	37,582	67,097	37,986	53,751	42,454
South	67,452	185,654	31,017	137,341	119,899
TWh					
World	9,987	11,477	9,987	12,738	7,192
North	4,885	3,643	4,908	4,139	1,796
South	5,102	7,834	5,079	8,599	5,396
Million tons (annual replacement)					
World	-	-	49	59	33
North	-	-	24	17	7
South	-	-	25	43	25

The results have several implications for policy and for research. As for policy, special attention should be given to the appliances with the highest energy consumption (portable air conditioners, refrigerators, water heaters, commercial and industrial refrigeration, etc.). It is particularly important to follow the growth in the demand for consumer goods in the Global South, and understand to what extent the population from this region can enjoy from efficiency improvements through, e.g., a wider dissemination of efficiency standards. Policies that phase out inefficient models have been effective particularly when there is an affordable alternative like in the case of phasing out incandescent light bulbs in lighting (e.g., Zissis & Bertoldi, 2018). On the other hand, policy could promote the sharing of equipment (air conditioner, ventilation, water heating, washing machines, tools, etc.) at the building level by removing legal and regulatory barriers or using instruments such as incentives or minimum requirements. Policymakers could also stimulate digital convergence of the devices by taking into account multi-functionality in the definition of efficiency standards or by supporting R&D partnerships on new converging devices following the model of development of LED lights in the past (DOE, 2012).

As for research, this study reveals promising directions to orient the efforts of the science and technology community to raise sustainability in consumer goods. On the one hand, the results point to key technical challenges that need further refinements and improvements in the coming years. For example, these efforts could focus on efficiency improvements, introduction of lightweight materials, development of product architectures enabling sharing and longer product lifetimes. On the other hand, the study shows the impact of possible discontinuities in the pursuit of the current technological trends. The ongoing digitalization of the objects opens new possibilities for improving energy efficiency and the provision of new services (e.g. smart

refrigerators which automatically order food). But the digitalization also accelerates the convergence between objects going up to substituting the physical devices (e.g. smartphones substituting the second TV set, DVD players, radios, …).

There are some limitations in our estimations. Firstly, we identify sharing potential by assuming the more widespread dissemination of localized practices (washing machines rooms at the building level in North America, student residences and co-living places for young and elderly in the Global North, etc.). More research is needed involving different perspectives (sociological, demographics, economics, etc.) on the potential for dissemination of these and other practices involving different segments of the population (single adults, monoparental families, etc.). Similarly, more studies are needed on the impacts of the digitalization of consumer goods and services. This assumes multiple ways (including connecting with other sectors like foods and transports) and can increase emissions in some applications (Wilson et al., 2020). Secondly, we took efficiency trends from LED and updated them with the most recent data to 2020. These data consider the long-term improvements in efficiency, but there are several accounts that the dynamics have slowed down in the past years (IEA, 2020b; Rousselot & Rocha, 2020). More research is needed to understand the reasons of this slowdown (consumer preference changes for larger devices, limits in the current product architectures, etc.) and the impact on the long-term assumptions for efficiency improvement. Finally, the estimates for material intensity and embodied energy base on numbers that are available in the literature and typical models of each category. High uncertainties remain about these values for specific regions, as well as for their evolution in the future with the introduction of both substantially different devices and new ones. These limitations point to relevant avenues for future research.

Appendixes

Appendix 1. Definition for the different levels of spatial disaggregation (Source: GEA, 2012).

Disaggregation on 2 regions *(e.g. LED scenario in Grubler et al., 2018)*	**Disaggregation on 5 regions** *(e.g. LED scenario in the 2019 version)*	**Disaggregatº on 11 regions** *(proposed now)*
Global North: Industrialized countries, i.e. OECD 90 and reforming economies. **Global South:** Developing countries, i.e. Middle East and Africa, Asia and Latin America and the Caribbean regions.	**OECD 90:** Countries that were OECD members in 1990, i.e. Western Europe, North America and Pacific OECD regions. **Reforming Economies (REF)**: Countries of Central and Eastern Europe and the Former Soviet Union undergoing economic reform. **Asia:** South Asia, Centrally planned Asia and China and Other Pacific Asia regions. **Middle East and Africa (MEA):** African and Middle Eastern countries that make up the Sub-Saharan Africa and Middle East and North Africa regions. **Latin America and the Caribbean (LAM):** Latin America and the Caribbean region.	**Sub-Saharan Africa (SSA)** **Centrally planned Asia and China (CPA)** **Central and Eastern Europe (EEU)** **Former Soviet Union (FSU)** **Latin America and the Caribbean (LAM)** **Middle East and North Africa (MEA)** **North America (NAM)** **Pacific OECD (PAO)** **Other Pacific Asia (PAS)** **South Asia (SAS)** **Western Europe (WEU)**

Appendix 2. Best fits of the correlations between number of devices per 100 persons (ownership) and GDP PPP per capita, in 2020, used to estimate the average ownership by device, by region, in 2050.

Lighting	*Type*	Fit Type	R2	a	b	t(max)
Residential	Lamps	logistics	96%	1593	0,000153	24876
Commercial	Lamps	logistics	92%	920	0,000247	21071
Hygiene	*Type*	Fit Type	R2	a	b	t(max)
Residential	Washing machines	logarithmic	86%	15	-125,22	
Residential	Water heaters	logarithmic	88%	16,55	-140,45	
Commercial	Washing machines	logarithmic	86%	7,50E-01	-6,261	
Commercial	Water heaters	linear	100%	0,0007	-2E-14	
Food preparation	*Type*	Fit Type	R2	a	b	t(max)
Residential	Refrigerator	logarithmic	98%	15,127	-123,35	
Residential	Freezer	potential	53%	0,0006	0,9568	
Residential	Stove	linear	77%	0,0007	-4,188	
Residential	Oven	linear	100%	0,0002	-4E-15	
Commercial	Commercial refrigeration	linear	100%	0,00004	1E-15	
Commercial	Stove	linear	100%	0,0004	4E-15	
Commercial	Industrial refrigeration	linear	100%	0,000003	4E-17	
Communication & entertainment	*Type*	Fit Type	R2	a	b	t(max)
Residential	Mobile phone	logarithmic	19%	5,65	26,653	
Residential	PC internet access	linear	89%	0,0019	-11,917	
Residential	Television	linear	77%	0,0007	8,957	
Commercial	PC internet access	linear	82%	0,0016	-10,045	
Commercial	Television	linear	77%	0,0007	8,957	
Thermal demand	*Type*	Fit Type	R2	a	b	t(max)
Residential	Fan	linear	55%	0,0007	3,0981	
Residential	Portable AC	linear	74%	0,0001	-0,017	
Commercial	Fan	linear	55%	0,0007	3,0981	
Commercial	Portable AC	linear	74%	0,00002	-0,0043	
Miscellaneous	*Type*	Fit Type	R2	a	b	t(max)
Residential	Misc	logistics	91%	171	0,000116	24863
Commercial	Power	linear	99%	0,00005	-0,0262	
Commercial	Heating	linear	39%	0,000005	0,0545	

The letters “a” and “b” refer to the parameters of the type of equations used in the best fits. For instance, a linear equation is $y=\boldsymbol{a}x+\boldsymbol{b}$ and a potential equation would be defined as $y=\boldsymbol{a}.x^{\boldsymbol{b}}$. The parameter “t(max)” refer to the third element of a 3 parameters logistic equation: $y=\boldsymbol{a}/(1+\exp(-\boldsymbol{b}(x-\boldsymbol{t(max)}))$, where “a” also indicates the saturation level and “t(max)” gives the level of revenue for which device ownership increases at its maximum rate.

Appendix 3. Services provided by appliances in 2020.

Sector	Category	Appliance	Number of devices	Service indicator	Service value
Residential	Lighting	Lamps	27631	billion lumens	18321
	Hygiene	Washing machine	1058	thousand tons of laundry washed	838
		Water heater	1029	trillion liters	31
	Food preparation	Refrigerator	1258	million cooled liters	372
		Freezer	430	million cooled liters	216
		(electric) Stove	549	billion BTUs/h	349942
		(electric) oven	185	billion BTUs/h	270112
	Communication	Television	1392	billion hours	2032
	& entertainment	Mobile phone	6167	billion hours of talk	7840
		Mobile phone		billion hours of web browser	3766
		Mobile phone		billion hours of video watching	3766
		Mobile phone		GWh of standby	10191
		PC (internet access)	1211	billion hours	972
	Thermal demand	Fan	1239	billion m3/minute	157043
		Portable air conditioner	117	billion BTU	692804
	Miscellaneous	Electric loads: set-top boxes, rooters, etc.	3230	billion hours	443
Commercial	Lighting	Lamps	18258	billion lumens	27926
	Hygiene	Washing machine	53	thousand tons of laundry washed	1270
		Water heater	842	trillion liters	620
	Food preparation	Commercial refrigeration	45	billion BTU/h	32
		Industrial refrigeration	4	billion BTU/h	200
		(electric) Stove	410	billion BTUs/h	523177
	Communication	Television	1392	billion hours	2032
	& entertainment	PC (internet access)	1163	billion units	1868
	Thermal demand	Fan	1239	billion m3/minute	157043
		Portable air conditioner	29	billion BTU	173201
	Productive uses	Power in agriculture, fishery, etc.	59	billion of hours	85
		Heating in agriculture, fishery, etc.	13	billion of hours	20
		Total	**69003**		

Appendix 4. Main inputs used in the analysis of the material requirements of the appliances

Category	Appliance	Steel (%)	Aluminium (%)	Plastic (%)	Mass (kg)	MJ/kg(raw)	MJ/kg(manuf.)	MJ/kg	Notes
Lighting	Lamps	0%	11%	10%	0,101	37	17	54	Babbitt et al., 2017
Hygiene	Washing machine	73%	5%	18%	60	46	17	63	Boustani et al., 2010
	Water heater	77%	2%	11%	30	39	19	58	Kemna et al., 2007
Food preparation	Refrigerator	56%	3%	28%	84	50	17	67	Boustani et al., 2010
	Freezer	0,28	9%	17%	69	78	12	90	assumed the same as small commercial freezers (equiv
	(electric) Stove					34	17	51	assumed the same as for domestic ovens (MJ/kg)
	(electric) oven	78%	5%	2%	28	34	17	51	Reale et al., 2019
Communication & en	Television	60%	0%	20%	12	39	98	137	Stobbe (2007)
	Mobile phone	26%	0%	39%	8	51	51	102	Babbitt et al., 2017
	PC (internet access)	12%	11%	27%	2	79	79	158	laptop
Thermal demand	Fan	24%	7%	34%	5	84	19	103	BRE, 2009
	Portable air conditione	35%	6%	61%	29	101	20	121	Room AC (smaller 7000 BTUs)
Miscellaneous	Small electric load devi	26%	8%	26%	8	56	56	112	Babbitt et al., 2017
Lighting	Lamps	0%	11%	10%	0,101	37	17	54	assumed similar to domestic lamps
Hygiene	Washing machine	73%	5%	18%	60	46	17	63	assumed similar to domestic washers
	Water heater	77%	2%	11%	30	39	19	58	Kemna et al., 2007
Food preparation	Commercial refrigerati	58%	5%	12%	119	42	14	55	Bio Intelligence Service, 2011
	Industrial refrigeration	28%	9%	17%	69	78	12	90	assumed similar to small commercial freezers (equivale
	(electric) Stove	77%	3%	7%	136	34	15	49	Bio Intelligence Service, 2011
Communication & en	Television	60%	0%	20%	12	39	98	137	Stobbe (2007)
	PC (internet access)	43%	2%	16%	19	45	45	90	desktop+LED display
Thermal demand	Fan	24%	7%	34%	5	84	19	103	BRE, 2009
	Portable air conditione	35%	6%	61%	29	101	20	121	Room AC (smaller 7000 BTUs)
Productive uses	Power in agriculture, fis	29%	0%	24%	0,25	105	15	120	Rota, 2020
	Heating in agriculture, fishery, etc.					101	20	121	assume similar intensity as portable AC

Sources (Appendix 4):

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Appendix 5. Data available in a separated Excel spreadsheet

The final spreadsheet will become available upon request and reasonable justification with detailed information about the assumptions and the results for the different scenarios. It will include an interface in which users can parameterize the main variables, and see the impact on the energy demand from consumer goods in 2050 (Figure S15). The interface will enable the parameterization of the DLS in terms of the number of devices per capita (or by household). Users could also define the maximum potential for digital convergence and sharing economy to respectively lower the energy intensity and the number of devices (Table S12).

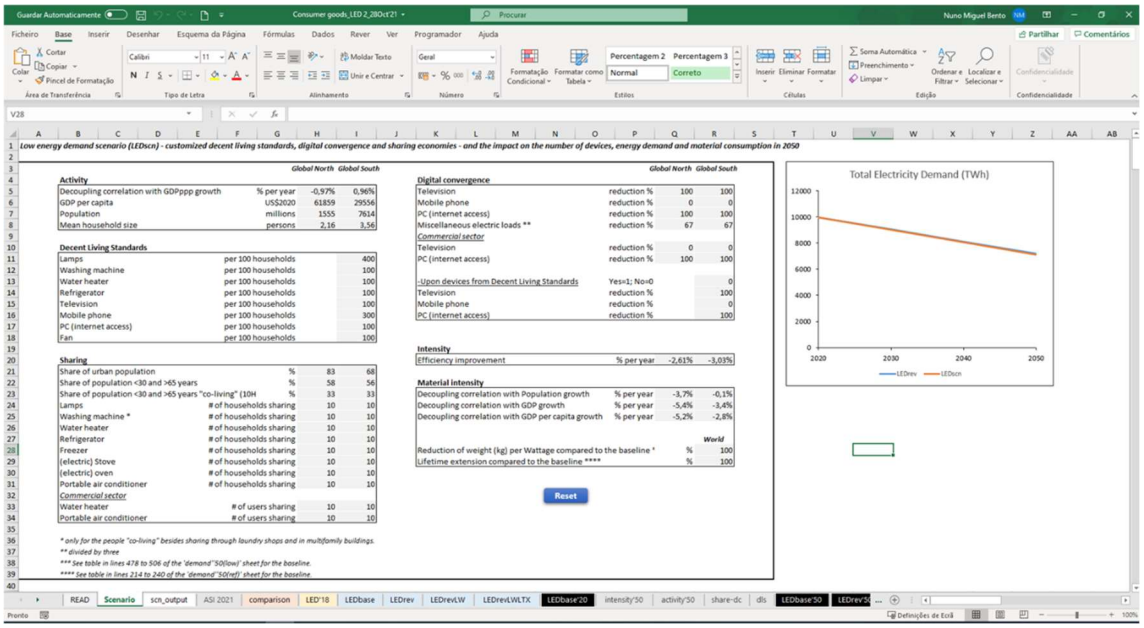

Figure S15. Interface of scenario generator featuring parameterizable key variables.

Table S12. Options to parameterize decent living standards, digital convergence and sharing economy in the interface

Categories of consumer goods	Decent Living Standards	Sharing economy**	Digital convergence***
Lighting	Number of lamps*	n.a.	n.a.
Hygiene	n.a.	Maximum potential for sharing washing machines, water heaters, dishwashers	n.a.
Food preparation	Number of refrigerators*, stoves*	Maximum potential for sharing stoves, refrigerators	n.a.
Communication and entertainment	Number of televisions*, PCs*, mobile phones	Maximum potential for sharing televisions, PCs	Maximum potential for digital convergence of television, mobile phone, PC (or internet device)
Thermal demand	n.a.		
Small electric load devices	n.a.		

* by household (HH), otherwise the number is per person.

** impacts mainly number of devices. Maximum potential for sharing is constrained (i.e. upper bounded) by the share of urban population living in multifamily dwelling, particularly in highly densified megacities.

*** impacts number of devices and energy intensity per device.

n.a.: not applicable.

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Leverage demand-side policies for energy security

Conventional supply-side approaches overlook potential benefits

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Energy security is a top priority for governments, companies, and households because energy systems and the critical functions that they support are threatened by disruptions from wars, pandemics, climate change, and other shocks (1). More often than not, governments rely on policies focused on energy supply to enhance energy security while generally ignoring demand-side possibilities. Further, the indicators traditionally used to measure energy security are also tilted toward the supply side; this fails to capture the full spectrum of vulnerability to energy crises. Energy security assessments need to reflect the wider benefits of security-related interventions more accurately. To that end, we develop a systematic approach to measuring the energy security impacts of policy interventions that explicitly considers energy demand (buildings, transport, and industry). We determine that demand-side actions outperform conventional supply-side approaches at making countries more resilient.

Energy demand links more directly than supply to the satisfaction of critical social functions and human well-being that are at the core of energy security. Yet, demand-side perspectives tend to be neglected or underrepresented in analysis and policy debates on energy security. Factors that contribute to this supply-side bias include the traditional sectoral organization of industries and policy institutions along fuels (coal, oil, and gas) and energy forms (electric utilities) as well as the decentralized and multivaried activities characteristic of energy demand (from vehicles to household appliances to manufacturing and more), which leads to a multitude of actors and institutional fragmentation. The basic fundamentals of energy systems and markets, where demand and supply are intricately linked, have also not yet risen from vague awareness to a central organizing principle among policy-makers for structuring the energy security discourse.

SUPPLY AND DEMAND IMBALANCE

The energy security literature describes a plethora of indicators and multi-indicator indexes. However, two-thirds of the indicators and more than 80% of the indexes focus on the energy supply side [see fig. S1 in the supplementary materials (SM)], aligned with the International Energy Agency (IEA) approach to define energy security solely as the security of energy supply (*2*). In addition, energy security analyses often rely on a small number of indicators, such as import dependency, diversity of energy sources (both produced and imported), or cost of energy imports as a proportion of gross domestic product (GDP) (*3*–*7*). In the few studies that also consider demand indicators of energy security [a noteworthy exception being (*8*)], these metrics are rarely quantified (see box S1 in the SM).

Not only is the structure of measures of energy security imbalanced, but the predominant indicators do not reflect the full picture. For example, a reduction in energy demand may leave a country's import dependence ratio unchanged—by simultaneously reducing both the volume of imports in the numerator and total energy consumption in the denominator. In this case, the unchanged ratio masks a marked reduction in the country's energy vulnerability—a smaller system being more flexibly satisfied from different sources—as well as benefits for the environment and trade balance.

Moreover, important gaps remain in the usage of indicators for energy security assessments. Some studies use scenarios for assessing future energy security (*9*). Others analyze the evolution of energy security in retrospect (*3*, *7*). To our knowledge, no assessment has yet combined scenario-based and historical analyses to determine the impact on energy security for different policy options. To be sure, demand-side indicators of energy security are neither perfect nor all-encompassing; still, they merit greater consideration for comprehensive energy security assessment.

FACTORS ENHANCING ENERGY SECURITY

Indicators used to measure energy security tend to emphasize supply diversification and substitution, costly storage, and redundancies in energy infrastructure. This overlooks the scale of vulnerability to energy crises; the benefits of energy demand reduction; and the energy cost burden to countries, firms, and households. Meanwhile, demand-side indicators more directly measure the satisfaction of individual needs and well-being because the focus is on access to and use of energy services. Examples of demand-based indicators of energy security include energy intensity of the economy (energy needed per unit of GDP), energy efficiency (the inverse of intensity), energy expenditures, and access to critical energy services (*10*). However, data availability can present a challenge to operationalizing the use of these indicators (*11*).

Illustrating the importance of including energy demand in energy security analyses, our analysis of Organisation for Economic Co-operation and Development (OECD) countries found a positive relationship [coefficient of determination ($R2$) = 11%, P = 0.08] between the ratio of energy expenditures to GDP and energy intensity (see fig. S2 in the SM). In other words,

countries with higher energy intensity (less energy efficient) tend to face higher energy cost burdens. We also found a robust negative correlation between energy intensity and the Shannon diversity index—a supply-side measure based on the diversity of a country's energy sources—for a set of 20 countries and macro regions ($R2$ = 48%, $P < 0.0001$, in 2014; $R2$ = 56%, $P < 0.001$, in 2019; see fig. S3, A and B, respectively, in the SM) (*12*). Put differently, a discernible trend between higher efficiency and diversification is evident across several countries over the past century (see fig. S3C in the SM).

Such analyses, possible only by including demand-side indicators, help in gaining a deeper understanding of the factors that reinforce or jeopardize a country's supply security. Yet, to our knowledge, such analyses have not been central to the scientific or policy discourses for many years.

COMPARING ENERGY SECURITY POLICIES

Four stylized policy interventions aimed at enhancing energy security are devised and their effectiveness is compared across a range of security indicators. Each of these aim at the same target, an ~10% change (reduction or reallocation) in total primary energy (i.e., unconverted natural resource inputs, such as coal, oil or gas, uranium, wind, or solar). These interventions are targeted at one of several points along the energy conversion chain: primary (PE), final (FE) (energy converted and delivered to end users—e.g., electricity or refined petroleum in the form of gasoline for vehicles), and useful (UE) (energy actually put to the intended use—e.g., the light resulting from the electricity used by a light-emitting diode light bulb).

We use an accounting model based on physical energy flows that first calculates conversion efficiencies throughout the energy system from primary to useful energy for specific end uses (mobility, thermal comfort, etc.). The model then calculates changes backward from useful to final to primary—e.g., reflecting how reduced gas use to provide low-temperature heat (useful energy) would affect the primary energy balance for gas and the corresponding potential to reduce gas imports (see box S2 in the SM for more details about the method and data). The four policies analyzed are import diversification (PE 1), fuel substitution (FE 1), reduction of low-temperature heat demand in buildings (UE 1), and transport electrification (UE 2) (see box S3 in the SM for more details about the policies).

An additional, somewhat extreme scenario estimates the impact on energy security of ensuring only the most basic energy services that guarantee critical social functions (CSFs) (minimum thermal comfort in buildings, transport, illumination, etc.). The CSF scenario assesses the ultimate social vulnerability of countries to energy crises and illustrates the upper potential of demand-side policies that is far larger than in the four other scenarios examined.

Historical analogies help to put the stylized policy measures into context and to demonstrate the order of magnitude of interventions (see boxes S3 and S4 in the SM). On the energy supply side, Germany's reduction of imports from Russia since the start of the war in Ukraine is an example of rapid import diversification that involved around a third of primary energy (PE 1). The Brazilian ethanol program illustrates fuel substitution (FE 1) that reached an impact

equivalent to 10% of primary energy. On the demand side, Germany's reductions of gas demand—mainly from buildings (UE 1)—saved 5% of primary energy in 2022. Sustained promotion of electric vehicles in Norway enabled a 10% reduction of primary energy in 2021, an example of the benefits of enhancing transport efficiency through electrification (UE 2). Similarly, the Corporate Average Fuel Economy (CAFE) standards in the US have saved more than 10% of primary energy over time (*13*). Finally, as an example of energy demand reduction from reduced activities, the COVID-19 response measures in the US led to a 7.5% decrease in primary energy in 2020 (*14*) (followed eventually by a rebound back to prepandemic amounts).

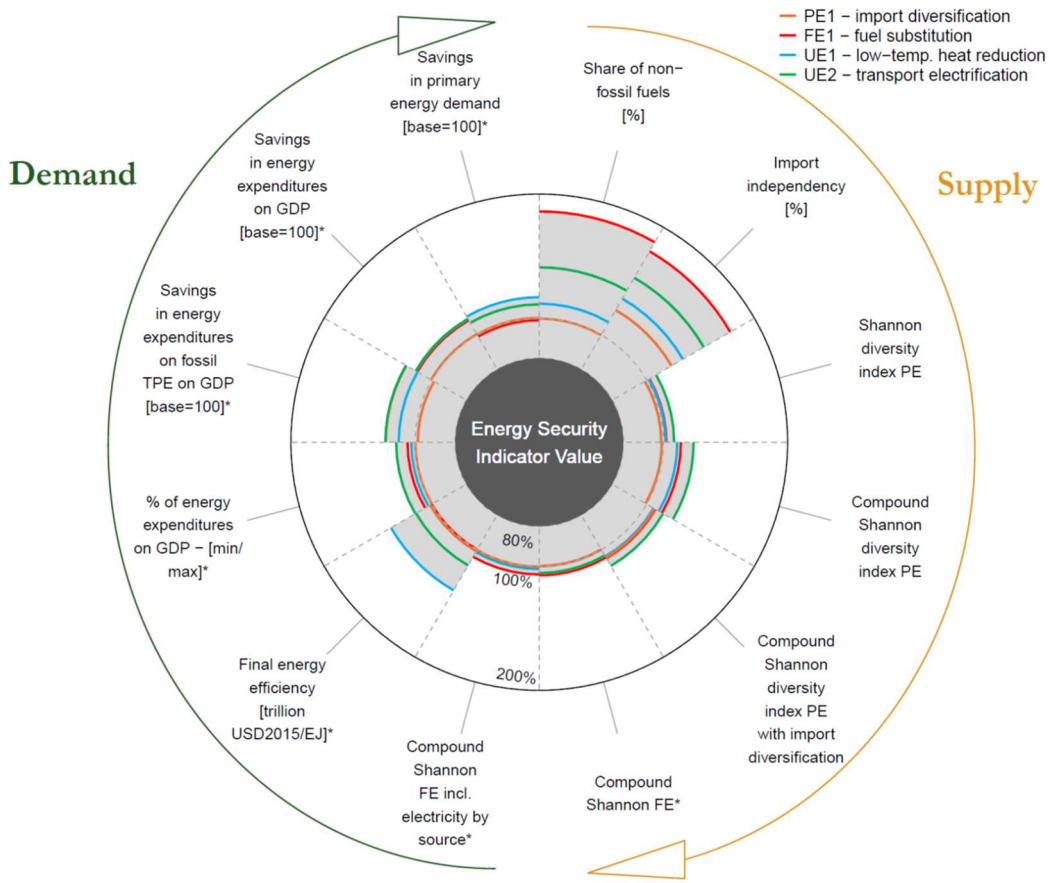
We use statistical data for a representative sample of 14 countries in 2019 to simulate the impact of the various policy interventions on national energy security. These countries account for two-thirds of global energy use in 2019 and include a diverse mix of high income and low income nations as well as energy importers and exporters (see SM). We quantify a set of 12 indicators of energy security from both demand and supply perspectives (see box S5 in the SM) to assess the impacts of each policy for each country. The choice of indicators followed three criteria: They must be representative, feasible to calculate, and complementary to each other. For example, four diversity indexes are included to assess different configurations of the energy system (e.g., different importing regions, different primary energy carriers, and different structures of energy demand).

To reach the same goal of changing 10% of primary energy, the four policies entail very different changes in energy flows at different points along the energy conversion chain (see the figure). A 10% change in primary energy (PE 1) required only a 9% change in final energy (FE 1) and only between a 5% and 3% change in useful energy level (UE 1 and UE 2, respectively), reflecting the corresponding conversion losses in energy systems. The difference is higher for exporting countries (see box S6 and fig. S4 in the SM). Overall, interventions at more-downstream levels benefit from a leverage effect by avoiding cascading losses in the successive stages of energy conversions.

The effects of the four stylized policy interventions for all indicators are presented separately (see the figure) for the average of the 14 countries in the assessment. Fuel substitution leads to the highest impact on only two indicators—the share of nonfossil fuels and import independency—confirming the bias against energy efficiency of these two popular energy security indicators. Demand measures score best in 8 of the 12 indicators, with transport electrification the most impactful (seven indicators). Import diversification is consistently the least effective intervention, despite being the most applied in Europe as a consequence of the Russian invasion of Ukraine.

National contexts influence the effects of the policy interventions (see the Table, as well as table S1 and fig. S5 in the SM). Transport electrification enhances energy security indicators the most (150 times) and only leads to worsening in 12 cases, whereas fuel substitution more often (29 times) deteriorates energy security, although it also improves it in 117 cases. Low-temperature heat demand leads to improvements in 137 cases and worsening in 23. Import diversification, although a commonly applied approach by governments, has a relatively muted effect—improvement in only 19 cases and worsening in nine.

Fig. 1. Impact of the policy interventions on enhancing energy security as shown by the 12 indicators. Indexed (base=100%). All policies aim at the same target (a 10% reduction in primary energy). Asterisk (*) identifies demand-side indicators.



Looking at four representative countries more closely (see fig. S6 in the SM), Japan and Australia (both high income economies) show a similar pattern, with transport electrification being the most effective policy. Meanwhile, Japan and China (both large energy importers) share more similar results than energy exporters such as Australia and Nigeria.

ROBUSTNESS OF DEMAND ACTIONS

An extensive sensitivity analysis that calculates every combination of the 12 security indicators (from 1 to 12 indicators in each combination; see fig. S7 in the SM) strongly supports the robustness of our conclusions. For example, there are only 6 of the 792 combinations (0.76%) that are possible to create with five indicators where fuel substitution is the most effective of the policies in improving energy security. Demand-side options and particularly transport electrification rank first in the remaining combinations.

Table 1. Effect of the policy interventions on 12 energy security indicators, in number of countries (n=14). Green shading indicates the number of countries where energy security improved based on the given indicator due the intervention (i.e., indicator value increases), red shading shows the opposite. Policy interventions appear in decreasing order of performance (i.e., improved indicators).

		Demand-side Policies		*Supply-side Policies*	
		UE 2 - Transport electrification	UE 1 - Low-temperature heat demand reduction	FE 1 - Fuel Substitution	PE 1 - Import diversification
SUPPLY INDICATORS	Share of non-fossil fuels [%]	14	9	14	-1
	Import independency [%]	13	9	13	0
	Shannon diversity index PE	8	6	5	0
	Compound Shannon diversity index PE	8	6	5	1
	Compound Shannon diversity index PE with import diversification	10	8	6	10
DEMAND INDICATORS	Compound Shannon FE*	11	3	9	-1
	Compount Shannon FE incl. electricity by source*	7	7	9	1
	Final energy efficiency [trillion USD2015/EJ]*	13	14	0	1
	% of energy expenditures on GDP - [min/max]*	14	13	13	-1
	Savings in energy expenditures on fossil TPE on GDP [base=100]*	12	11	10	-2
	Savings in energy expenditures on GDP [base=100]*	14	14	12	1
	Savings in primary energy demand [base=100]*	14	14	-8	1
	total (improved net of worsened)	**138**	**114**	**88**	**10**
	of which: total (improved)	150	137	117	19
	total (worsened)	12	23	29	9

Our multidimensional indicator and policy modeling framework also allows for testing alternative policies beyond the four described above. For example, when considering a representative energy importer nation, such as Japan, fuel substitution (FE 1) with hydrogen (also domestically produced) instead of biofuels leads to a similar level of impacts on energy security for all indicators but lower final energy efficiency and lower savings in energy expenditures (i.e., hydrogen increases primary energy use and energy costs). Similarly, rolling out heat pumps instead of insulation (UE 1)—in this case, an active measure in place of a

passive one—to reduce energy demand for low-temperature heat for buildings in Japan would not ameliorate the energy security indicators (see fig. S8 in the SM). The variations of the policies tested in the sensitivity analysis confirm the robustness of the order of merit of the interventions: Demand-side policies generally have more and higher positive impacts on improving energy security compared with supply-side measures.

Assumptions for fuel substitution with biofuels are quite optimistic. For example, not every country has enough available biomass, not to mention the potential land-use conflicts with agriculture and environmental concerns. Yet, even under these assumptions, demand-side policies remain the top choice in most cases. It is also worth noting that the higher scores of transport electrification compared with reducing low-temperature heat demand in buildings benefit from our assumptions that the needed electricity for transportation comes from domestic renewable sources. If, instead, this electricity is generated from, for example, imported natural gas, the policy would be less efficient compared with other policies.

The overall ranking of policy options also holds when looking at key indicators beyond energy security, namely carbon dioxide emissions reductions (see fig. S9 in the SM). For the four archetypal policy cases analyzed, demand-side policies again outperform supply-side policies (0% for PE 1 and -11% for FE 1 against -12% for UE 2 and -13% for UE 1), even if the ranking order of transport electrification over heating demand reduction reverses. The ultimate potential of demand-side policies is illustrated in the (extreme demand reduction) CSF scenario (-67%).

CONCLUSIONS

Demand-side policies offer clear advantages for energy security improvement across many dimensions, including continuity, affordability, and sustainability. They also have advantages in terms of flexibility. Demand-side policies give more opportunities for intervention at the national level, relative to fuel substitution, for example, which requires international coordination. Energy security is more than security of supply because there are other economic, social, and environmental aspects that are also relevant. Future studies should compare the benefits of different energy security policies more systematically by including a demand-side perspective instead of relying on partial assessments and problematic indicators, such as import dependency. They could also expand to encompass a more comprehensive assessment of the social and environmental effects. This approach would contribute to a more nuanced understanding of energy security and inform more effective policy decisions on both a national and a global scale.

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SUPPLEMENTARY MATERIALS

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Science
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Supplementary Materials for

Greater leverage for energy security with demand-side policies

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The PDF file includes:

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Supplementary Text
Boxes S1 to S4
Figs. S1 to S7

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Supplementary Materials (SM).

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Indicator	Kruyt et al. 2009	Sovacool & Mukherjee 2011	Winzer 2012	GEA 2012	Jewell et al. 2014	Ang et al. 2015	Kisel et al. 2016	Gasser, 2020
Energy intensity of the economy	○	○		●	●	○		○
Energy affordability	●	○				○		○
Energy efficiency	⊙	○			⊙	○		○
Capacity of energy storage	○			●		○	○	
Access to modern energy services		○		●		○		○
Vulnerability to energy shocks	○	○	●	●	○	○	○	○
Diversity of supplies in end-use sectors	○	○			○	○	○	○

Sources : Kruyt et al. 2009 (*4*) ; Sovacool & Mukherjee 2011 (*5*) ; Winzer 2012 (*6*) ; GEA 2012 (*10*); Jewell et al. 2014 (*9*) ; Ang et al. 2015 (*7*) ; Kisel et al. 2016 (*11*) ; Gasser, 2020 (*3*).

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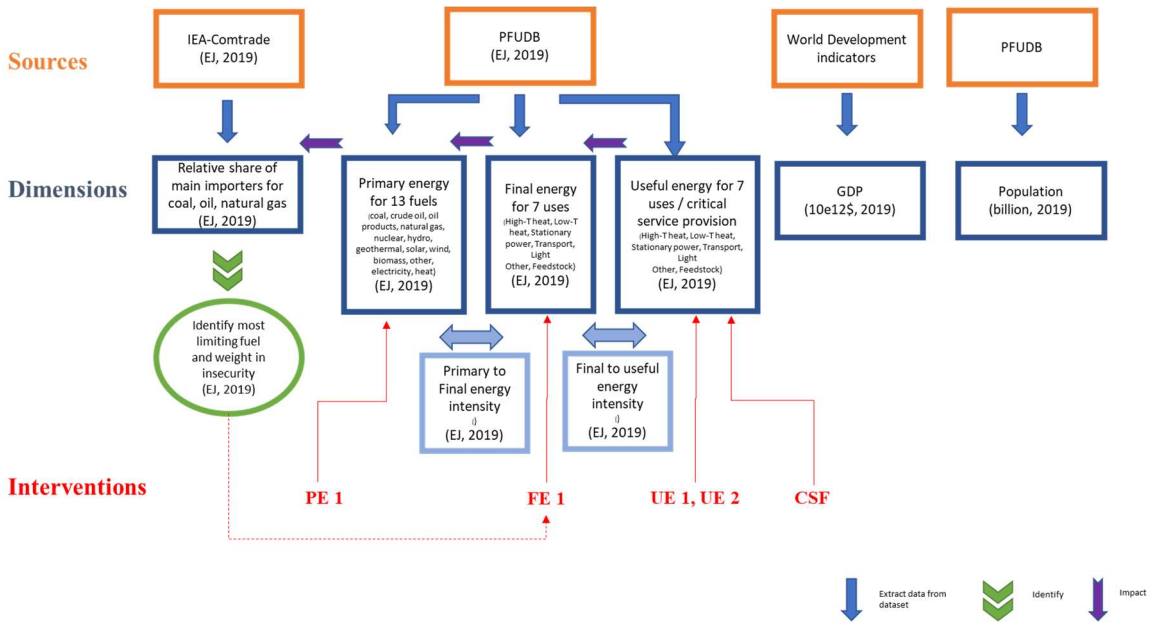
box S2. Data and methods



scheme S1. Flow-chart describing the procedure followed in this study.

Our methodology follows several stages to compare the effects of different types of policy interventions. Scheme S1 summarizes the main stages. We explain the procedure around the three main stages: data extraction from original sources and preparation: estimation of the indicators for 2019 (base case) by considering the relevant dimensions of the data; simulation of the policy interventions' impact and comparisons.

Data extraction and preparation

The data for the analysis comes from multiple sources covering different dimensions. We list here the main sources:

- PFUDB - Primary, Final and Useful Energy Database (*12*);
- IEA's World Energy Balances (*14*);
- COMTRADE: UN COMTRADE (*15*), BACI (*16-17*);
- World Development Indicators: World Bank (*18*).

The PFUDB database provides country-specific data on primary energy (PE), final energy (FE) and useful energy (UE). The IEA's World Energy Balances gives the origin (domestic production or imports) of the energy sources across countries. UN COMTRADE dataset and the modified BACI-Comtrade database contains trade data on energy imports and exports by source (oil, natural gas, etc.) and by country of origin and destination, both in physical and monetary

terms. World development indicators provide countries' socioeconomic numbers such as the GDP.

We assemble the datasets by country and fulfill the relevant dimensions needed to calculate the indicators of energy security. From the PFUDB database, we obtain the PE for 13 fuels (coal, crude oil, oil products, natural gas, nuclear, hydro, geothermal solar, wind, biomass, other electricity, heat). We further take the FE and the UE for 7 uses (high-temperature heat, low-temperature heat, stationary power, transport, light (illumination), other). The PFUDB also provides the data for the countries' population. From the IEA and the COMTRADE data, we identify the relative shares of the main energy importers for coal, oil and natural gas. It is important to note that data is reported on direct equivalent in PE for all non-fossil energy carriers, which is markedly different from the so-called substitution equivalent accounting method that artificially inflates the primary energy equivalent of non-fossil electricity generation.

Estimation of base case indicators

We calculate a set of 12 energy security indicators per country for the year of 2019 (see more details in Box 1). We also estimate the indicators for the year 2014 as a further sensitivity analysis. We perform the calculations in an Excel spreadsheet with a standardized format used for all countries in the sample. The spreadsheet computes the result of the indicators automatically based on the provided data. The estimations for the year 2019 serve as the base case for comparing the results of the different policy interventions.

Simulation of policy interventions and comparisons

The objective is to assess the policy impact of measures corresponding to 10% primary energy demand (e.g., equivalent to 9 EJ in the US or 2 EJ in Japan). When such measures are implemented at final or useful energy levels, the figures are adjusted downwards by the respective efficiencies of FE/PE or UE/PE conversion (see Box 3. for more details). At the end, we calculate the energy security indicators and compare the policy intervention based on the results for the indicators.

To reach the 10% PE target, we compare four (4) policy interventions and one scenario (CSF):

- PE 1: supply-side, import diversification (all the rest remains the same as in the base case);

- FE 1: supply, oil to biofuels (domestically produced) substitution in transport at the final energy level;

- UE 1: demand, reduction of the useful energy demand for low-temperature heat in buildings (e.g., via insulation);

- UE 2: demand, reduction of useful energy demand in transport through substitution of conventional combustion vehicles by electric vehicles (transport electrification);

- CSF: critical social functions (energy services needed to maintain vital energy services that support critical social functions at a sufficiency level or enough to guarantee decent living standards for all in developing countries).

We simulate the effects of each policy intervention following the procedures described in the next paragraphs.

PE 1 – import diversification away from the two largest importers

To implement the import diversification scenario while keeping other variables unchanged, we implement the following steps using trade values (of fossil fuels) from the BACI-COMTRADE database.

We identify the largest fossil fuel import (usually oil). Then we reduce import flows from the two largest sources to 0. We calculate the concentration ratio (CR2) using the shares of the 3rd and 4th original largest import sources. This ratio is then used to calculate the compound Shannon indexes. The imports from the original two largest sources are allocated to the category "other import sources".

FE 1 – reduction of ~10% PE equivalent in final energy (FE) demand for transport through fuel substitution (oil to biofuels)

We start by reducing the part of oil in transport FE demand by an amount equivalent to 10% PE considering the relative transport oil efficiency (i.e., FE/PE). That is, the reduction will be slightly lower than 10% PE due to the conversion losses (from PE to FE) avoided given the reduction of the transport FE demand.

Then, we increase the FE demand for biofuels in transport proportionally to the reduction in oil. We propagate the changes to the PE level using the current efficiencies for oil and biomass in transport. In the cases where there are no transport biofuels available, we assume a PE to FE conversion efficiency of 75%, based on the best-case scenario for Brazilian ethanol and US corn ethanol. Lastly, we update the PE production numbers for biofuels and adjust the import numbers to reflect the reduction in oil consumption.

UE 1 – reduction of ~10% PE equivalent in useful energy (UE) demand for low-temperature heating (e.g., through better insulation of building envelopes)

We decrease the UE demand for low-temperature heating from fossil fuels—including oil, gas, and biomass, and coal where appropriate. The amount of reduction corresponds to 10% of PE equivalent, that is multiplied by the ratio UE/PE of low-temperature heat efficiency. The reduction is allocated among the different fuel sources (usually oil and natural gas) to minimize fossil fuel imports.

We propagate the changes to FE and PE levels using corresponding fuels-specific low-temperature heat efficiencies (from base case). Finally, we adjust imports (and production if needed) to ensure consistency with the modified energy balance.

We note that the impact of this policy can be relatively modest, particularly for conventional supply-side energy security indicators such as independence ratios, as both imports and PE are scaled down proportionally. For that reason, we consider one alternative policy case involving the reduction of UE demand for low-temperature heating of 10% PE equivalent through improved insulation and subsequently supplying all the remaining energy needed through electric heat pumps with a high efficiency of 300% in converting FE to UE. We additionally assume that all additional electricity required could be generated from domestic renewable sources, similarly to policy UE 2 (transport electrification, see next). This alternative intervention is considered for sensitivity analyses (see the results for Japan in fig. S7).

UE 2 – reduction of UE in transport to the equivalent of 10% PE via electric vehicles

We start by reducing the UE demand for oil in transport by 10% of PE multiplied by the UE/PE efficiency. Then we increase the UE demand for electricity in transport by the same amount.

We propagate the changes to FE by using existing transport UE/FE efficiencies for oil, and assuming an efficiency of 100%, i.e., UE=FE, for electricity. (Different assumptions for losses were tested with non-substantial impacts.) Next, we propagate changes from FE to PE. For that, we again assume transport FE/PE efficiencies for oil and no losses for electricity. We allocate additional electricity uniformly across all non-fossil domestic electricity options (even if current production is 0). Finally, we adjust the PE balance by the additional inputs to electricity generation (using the direct equivalent PE accounting method) and correct oil import flows and PE production to be consistent with the modified energy balance.

CSF – critical social functions

We calculate the energy requirements of critical social functions by scaling down current demand (applying adequate multipliers). That is, primary, final and useful energy needs for critical social functions are estimated as a proportion of the current total consumption. CSF excludes industrial energy uses (high-temperature heat, stationary power [industrial drives] and petrochemical feedstocks). CSF fractions were determined iteratively, by comparing the results of different scaling factors (or multipliers) in terms of their resulting aggregate energy consumption per capita (GJ per year) and considering sufficiency levels for the OECD countries. Given the energy demand of many developing countries remains low with large segments of the population underserved with modern energy services, the multipliers are different for these countries to guarantee that these countries remain above the threshold levels given in the literature on decent living standards (e.g., *19*). The table shows the multipliers that are used to scale down the energy balances for determining CSF:

Multipliers (PE-FE-UE)	Non-OECD	OECD
High-Temperature heat	0	0
Low-Temperature heat	0.75	0.5
Stationary power	0	0
Transport	0.5	0.25
Light	1	1
Other	1	1
Feedstocks	0	0

With these assumptions, the CSF values are aligned with representative sufficiency and decent standards of living values across OECD and non-OECD countries (i.e., ranging from >9 GJ/capita FE in India to ~60 GJ/capita FE in the USA).

We propagate the changes to production and import flows by assuming that the lowered demand of CSF first leads to reduce imports and then to lower domestic production. That is, if the countries' domestic production is larger than CSF PE demand (by source), imports are set to 0 and domestic production is adjusted accordingly.

Final remarks on the propagation of demand changes to the supply-side (production, imports and exports):

We correct the PE (supply) balances by the difference between the demand per source in the base case (year 2019) and under the policy intervention considered, through the following procedure:

1. first reduce imports;

2. if demand reduction is larger than imports, decrease domestic production;

3. only if demand reduction is larger than imports and production (steps 2 and 3 are not enough), reduce exports.

The 3rd step is the last resort as exports are an important source of revenues for developing countries. Non-OECD countries need foreign currency revenues as they have little industrial exports.

Finally, in the cases where PE demand *increases* per source (such as a growth in renewable energy sources in UE 2 – transport electrification), we proceed as following:

4. start by reducing exports;

5. if demand increase is higher than exports, then allocate the remaining to (increasing) domestic production;

6. do not change imports.

Auxiliary calculations for estimating the energy security indicators (energy expenditures, etc.):

Energy expenditures in 2019 are estimated by taking the prices from COMTRADE (e.g., coal, oil, natural gas, electricity). Prices are converted from $/MWh to $/1000 MJ units to make them more comparable. In the case of electricity, and for isolated countries (e.g., Australia), we search for wholesale prices (without taxes) from different available sources (official national sources, IEA, etc.).

Decadal variance on annual energy prices is identified to calculate the share of energy expenditures on GDP under minimum and maximum decadal prices (between the years 2012 to 2021). For coal, oil and natural gas, energy prices come from BP (*20*). Electricity prices are from IEA (*21*). We consider the electricity prices at the end-use level (for households) net of taxes. We use the same net prices for all the electricity generation as a proxy of the opportunity costs of production independently of the primary source. Finally, biomass is valued at the price of the cheapest PE (coal) for all countries, OECD or developing countries.

box S3. Illustrative policy interventions with real-world examples. Includes four policy interventions with equivalent effect to 10% change in primary energy use and a scenario aiming to provide for critical social functions only.

Code	Policy	Detail	Examples of real-case policies
PE 1	import diversification	reducing the import flow of the two largest energy importers up to 10% of primary energy and obtaining this flow from the 3rd and 4th largest providers	EU countries imposed sanctions on Russian crude oil and refined petroleum products following the Russian-Ukraine conflict. For example, Germany sharply reduced the imports of oil and gas from Russia, representing around 10% and 24% of total primary energy in 2021 respectively, to nearly 0% in early 2023 (22). This amounts to a total displacement of around 4 EJ or a third of the country's primary energy consumption (see also Box S4).
FE 1	fuel substitution	substituting imported oil with domestic biofuel (biomass) by increasing production proportionally to the policy target (10% of primary energy)	The Brazilian ethanol production reached its peak in year 2019 with 35 billion liters (*23*). This equates to 1.2 EJ or 10% of total primary energy of Brazil in 2019.
UE 1	reduce low-temperature heat	reducing the low temperature heat demand of residential and commercial buildings through, e.g., better insulation of walls or installation of efficient windows	EU countries approved emergency laws in the outset of the Russian invasion of Ukraine to reduce gas consumption by 15% in 2022. In Germany, for example, immediate demand reductions in response to the Ukrainian War (through a mix of behavioral change, policy and warm temperature) led to a reduction of -14% in gas demand in 2022 compared to the 2018-2021 average, or about 5% of primary energy (*22*)—(24) reports higher reductions (-22%) in gas consumption in the 2nd half of 2022.
UE 2	transport electrification	reducing the energy demand in transport via the electrification of transport modes	Norway approved a mandate to have 100% of zero-emission vehicles sales in 2025, thereby banning Internal Combustion Engines by that time. In 2023, Norway keeps VAT exemption and subsidy schemes for new EV sales. As a result of purchase incentives and infrastructure deployment, EVs already represented 17% of the car park and 88% of new sales in Norway, at the end of 2022 (*25*). This contributed to a reduction in gasoline consumption of around 0.02 EJ or 10% of primary energy in the last decade (*26*). In the US, CAFE fuel consumption standards reduced oil demand by 200 EJ between 1975 and 2018 or on average by 5 EJ per year (*18*). In 2018 this effect was estimated to amount to 10.3 EJ or 10.7% of primary energy (*13*, *26*).
CSF	critical social functions	energy services necessary to ensure critical social functions (minimum thermal comfort in buildings, transport, etc.)	The net COVID effect on PE consumption in the US in 2020 was -7.9 EJ or -7.5% (*26*). The French Energy Sobriety Plan aims to reduce final energy consumption in 10% by 2024 and 40% between 2022 and 2050.

box S4. Effects of the German response to the energy crisis

The share of Russian gas in the German gas mix has decreased from 52% in 2021, via 22% in 2022 to 0% in early 2023 (*22*). This translates to a reduction from around 24% in 2021 to 0% of PE in 2023, with a total substitution of around 3 EJ of Russian gas (*22*, *27*).

In addition, the share of Russian oil in the German oil mix decreased from around 35% before the war (2021/2022) to close to 0% in early 2023 (*28-29*). This translates to a reduction from close to 10% of PE (~1 .1 EJ) in Russian oil to 0%.

In Germany, for example, immediate demand reductions in response to the Ukrainian War (through a mix of behavioral change, policy and temperature) led to a reduction of -14% in gas demand in 2022 compared to 2018-2021 average, about 5% of PE (*22*).

box S5. List of energy security indicators surveyed

Indicator	Unit	Energy security dimensions	Energy security issues	Definition and formula	Energy system level
Energy-Supply indicators					
Share of non-fossil fuels	%	Sustainability	Climate and geopolitical risks	Share of coal, oil and nat.gas in total primary	PE
Import independency	%	Continuity	Risk of trade disruption	Energy import divided by total primary energy	PE
Shannon diversity index PE	Non-dimensional	Continuity	General vulnerability to disruptions in energy import	Shannon–Weaver Diversity Index (SWDI)	PE
Compound Shannon diversity index PE	Non-dimensional	Continuity	Weighted dependence in diversity issues	SWDI adjusted for net imports	PE
Compound Shannon diversity index PE with import diversification	Non-dimensional	Continuity	Weighted dependence to major energy importers in diversity issues	SWDI adjusted for concentration ratio (CR2)	PE
Energy-Demand indicators					
Final energy efficiency	EJ/trillion USD2015	Affordability, Sustainability	General vulnerability to price and supply disruptions	Total final energy divided by GDP	FE
Compound Shannon FE	Non-dimensional	Continuity	General vulnerability to disruption in energy carriers	SWDI using FE shares	FE
Compound Shannon FE incl. electricity by source	Non-dimensional	Continuity	General vulnerability to energy carriers disruptions and limited switching	SWDI using FE shares and electricity sources	FE
Share of energy expenditures on GDP - [min/max]	%	Affordability	Price change risk	Relative size of energy expenditures estimated with decadal maximum and minimum prices	FE
Savings in energy expenditures on fossil TPE on GDP	index (base=100)	Affordability, Sustainability	Vulnerability to climate and trade disruptions on fossil fuels	Policy impact on reducing the share of GDP non-devoted to expenditures on fossil fuels	PE
Savings in energy expenditures on GDP	index (base=100)	Affordability	Vulnerability to energy burden increase due to energy crisis	Policy impact on reducing the share of GDP non-devoted to energy	PE
Savings in primary energy demand	index (base=100)	Continuity, Sustainability	General vulnerability due to increasing exposure to energy supply and prices disruptions	Policy impact on reducing primary energy consumption	PE

box S6. List of countries and policy impacts

Energy impact matrix – in EJ

EJ	PE (2019)	10% PE target	PE 1 import diversification	FE 1 fuel substitution	UE 1 low-temp. heat	UE 2 transport elec.
Australia	6.0	0.60	0.60	0.55	0.24	0.18
Brazil	12.4	1.24	0.75	1.19	0.53	0.22
Canada	12.4	1.24	1.24	1.06	0.59	0.35
China	140.6	14.06	7.35	12.89	6.94	3.67
France	7.6	0.76	0.76	0.74	0.50	0.24
Germany	12.2	1.22	1.22	1.14	0.78	0.37
India	38.4	3.84	3.84	3.55	1.12	0.61
Italy	6.4	0.64	0.64	0.66	0.39	0.19
Japan	17.1	1.71	1.71	1.62	1.01	0.53
Nigeria	6.6	0.66	0.35	0.66	0.08	0.07
Poland	4.4	0.44	0.44	0.43	0.22	0.19
South Africa	5.9	0.59	0.59	0.57	0.12	0.11
United Kingdom	7.2	0.72	0.72	0.67	0.45	0.22
United States	88.9	8.89	8.89	8.40	5.04	2.97
Average	26.2	2.62	2.08	2.44	1.29	0.71
Min	4.4	0.44	0.35	0.43	0.08	0.07
Max	140.6	14.06	8.89	12.89	6.94	3.67

Sources PE: PFUDB 2023 (*12*), IEA 2023 (*14*).

Energy impact matrix – index (10% PE target=100%)

Index	10% PE target	PE 1 import diversification	FE 1 fuel substitution	UE 1 low-temp. heat	UE 2 transport elec.
Australia	100%	100%	91%	41%	31%
Brazil	100%	61%	96%	43%	17%
Canada	100%	100%	85%	47%	28%
China	100%	52%	92%	49%	26%
France	100%	100%	97%	65%	32%
Germany	100%	100%	94%	64%	30%
India	100%	100%	92%	29%	16%
Italy	100%	100%	103%	61%	29%
Japan	100%	100%	95%	59%	31%
Nigeria	100%	53%	100%	13%	11%
Poland	100%	100%	98%	50%	43%
South Africa	100%	101%	98%	21%	19%
United Kingdom	100%	100%	93%	63%	31%
United States	100%	100%	94%	57%	33%
Average	100%	91%	95%	47%	27%
Min	100%	52%	85%	13%	11%
Max	100%	101%	103%	65%	43%

In our energy security analysis, we considered 14 individual countries—the sample of 15 countries from above, minus Former Soviet Union which was not analyzed because of the breakup of the Soviet Union into individual countries that do not pursue the same energy policies. Altogether, these 14 countries represent about two thirds (63% of primary energy, 62% of final energy, and 66% of useful energy) of the world energy use in 2019, and thus they are very representative of the world situation.

This sample size was chosen to be consistent with the PFUDB sample used for the long-term historical analysis. The policy analysis reported here, in principle, are replicable for any other country for which energy balances are available from the IEA.

We include the five largest energy systems (China, US, India, Japan, Germany) as well as, in addition larger representatives of each continent (Brazil, Canada, France, South Africa, Nigeria, Australia), and the remaining countries that are covered in the PFUDB (United Kingdom, Italy, Poland) to ensure consistency between our historical analysis (fig. S3) and the policy analysis at the national level.

The tables above show the impact of the policy interventions to reach the same target of 10% of the focal country's primary energy (PE). Interventions at final energy (FE) and useful energy (UE) levels are smaller since conversion losses increase the effect at the PE level. For example, in average, to change 10% of primary energy of the countries in the sample or 2.62 EJ, only 2.44 EJ change is needed at the FE level and only 0.71 EJ if the policy is implemented at the UE level in case of transport electrification. These are respectively 95% and 27% of the target value (2.63 EJ). (The policy intervention "PE 1 – import diversification" is not comparable as it deals with diversifying the two largest energy import sources of the country that may not total 10% of PE as the case in Brazil, China, or Nigeria.)

The intervention at PE level of 10% results in 90% of PE staying unchanged and 10% being adjusted, e.g., relocation of imports (PE 1), replacement of 10% of PE oil imports by domestic biomass based transport fuels (FE 1). Propagation of the interventions at the different levels can vary depending on the sectors and primary energy sources involved—as explained in Box 2. In short, interventions at the UE and FE levels propagate upstream to PE, impacting the energy mixes and imports. This propagation considers the efficiency differences in PE-to-FE or FE-to-UE, by taking into account the specific contributions of each subsector to total final/useful energy of the country under analysis.

Additional assumptions had to be made for the cases in which there was not enough demand at UE or FE levels to reach the 10% target at PE. In these cases, the reduction in demand could not be larger than the respective total UE or associated FE demand. For example, some developing countries (e.g., Nigeria) have so low useful energy in transport that the reduction cannot be so large as to yield 10 EJ at PE. In these cases, the policy impact was constrained to not exceed the actual demand in the demand category considered. This was the case for FE 1 thermal demand from Residential and Commercial buildings (Australia and Brazil) and for UE 2 transport (China, India, and Nigeria).

fig. S1. Number of indicators and indexes (i.e. composite indicators) of energy security by type in the literature. Sources: Authors' elaboration using indicators and indexes proposed in Sovacool & Mukherjee (*5*), Jewell et al (*9*), Gasser (*3*) and Ang et al. (*7*).

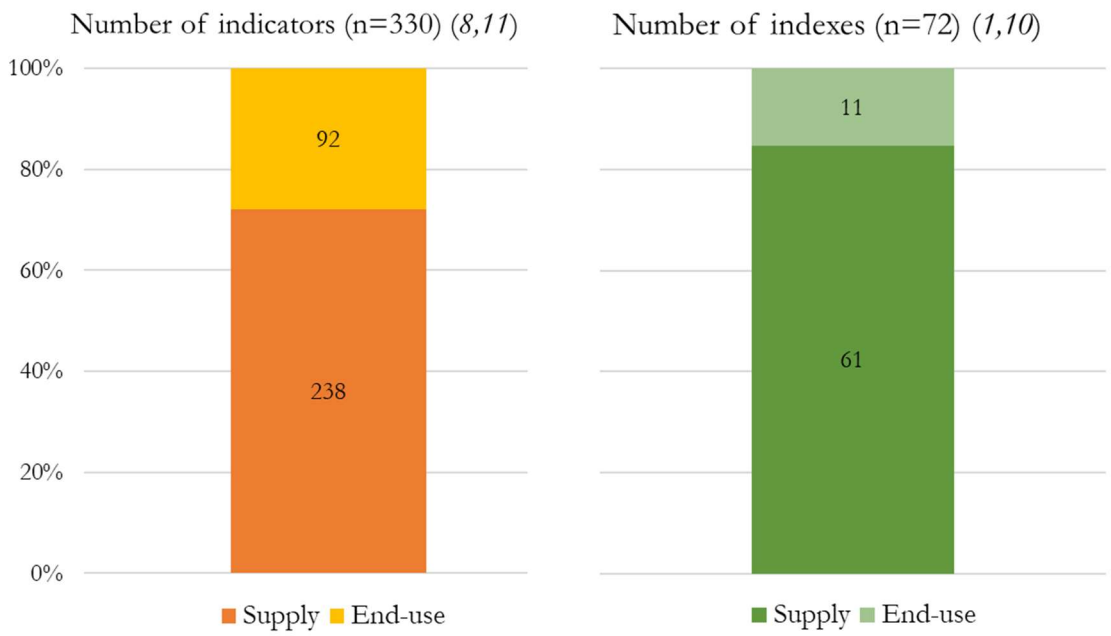


fig. S2. Energy intensity and shares of energy expenditures on GDP, OECD countries in 2019.
Source: IEA (*14*); OECD (*30*). TFC: total final consumption (primary energy).

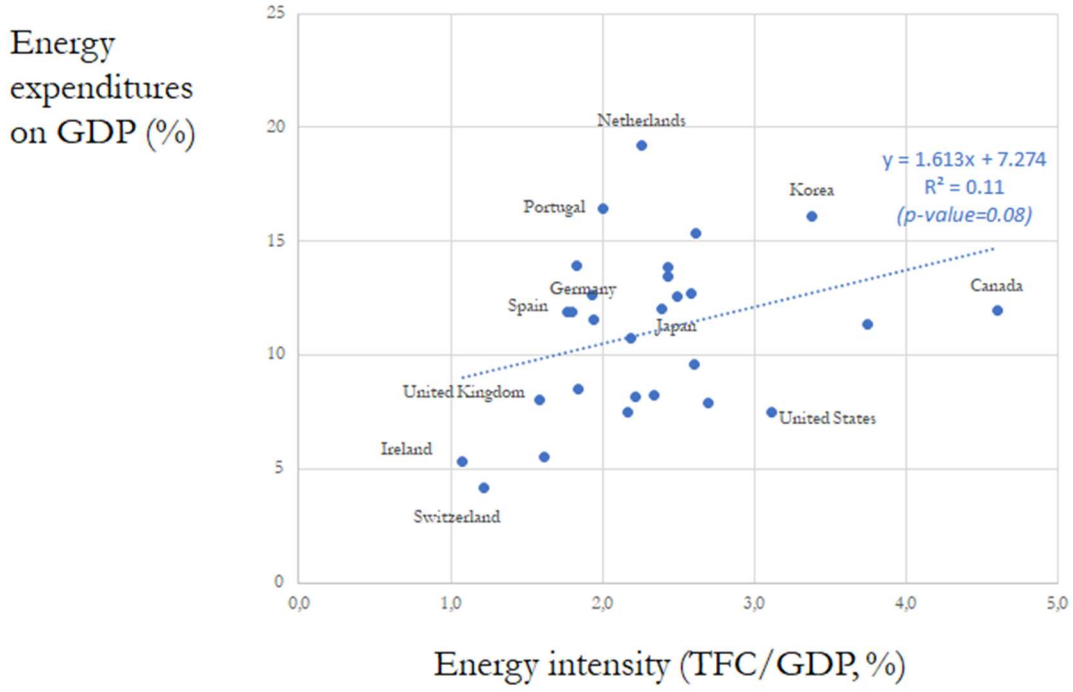
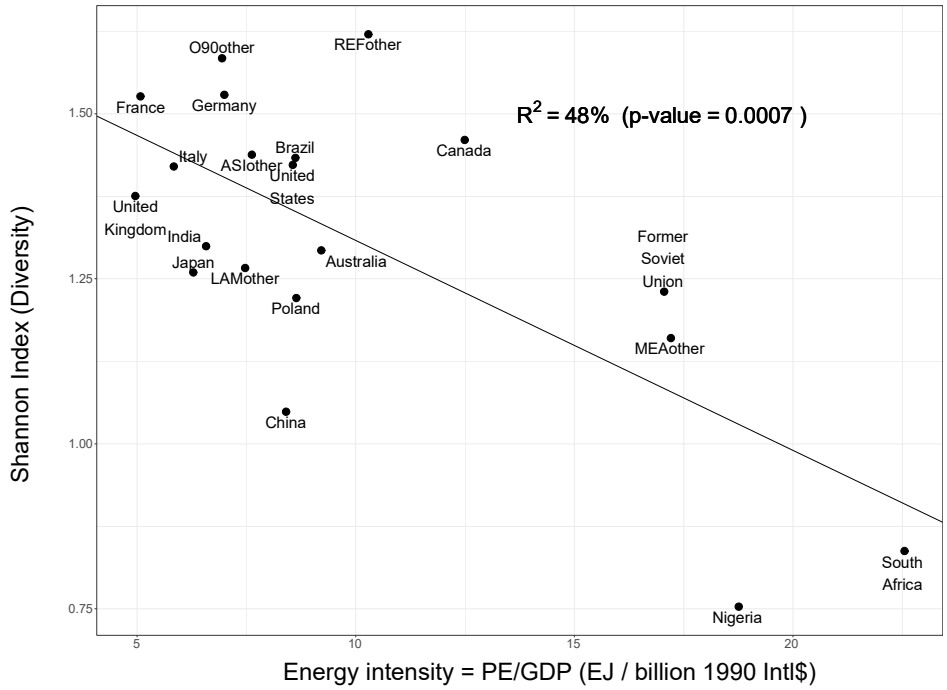
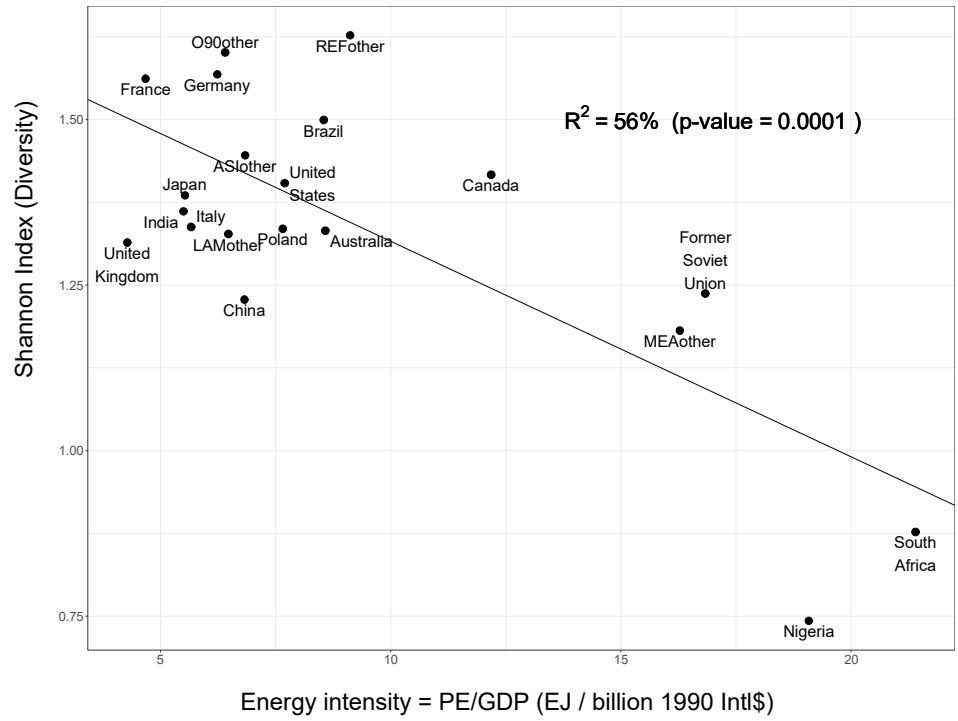


fig. S3. Energy intensity and diversity of primary energy sources (Shannon Index). Developed, developing countries and macro regions (n=40) from the PFUDB database (19) in 2014 (**A**), in 2019 (**B**), and six countries between 1900 and 2020 (**C**). Source: (*12*).

A. Static correlation 2014



B. Static correlation 2019



C. Dynamic correlation 1900-2020

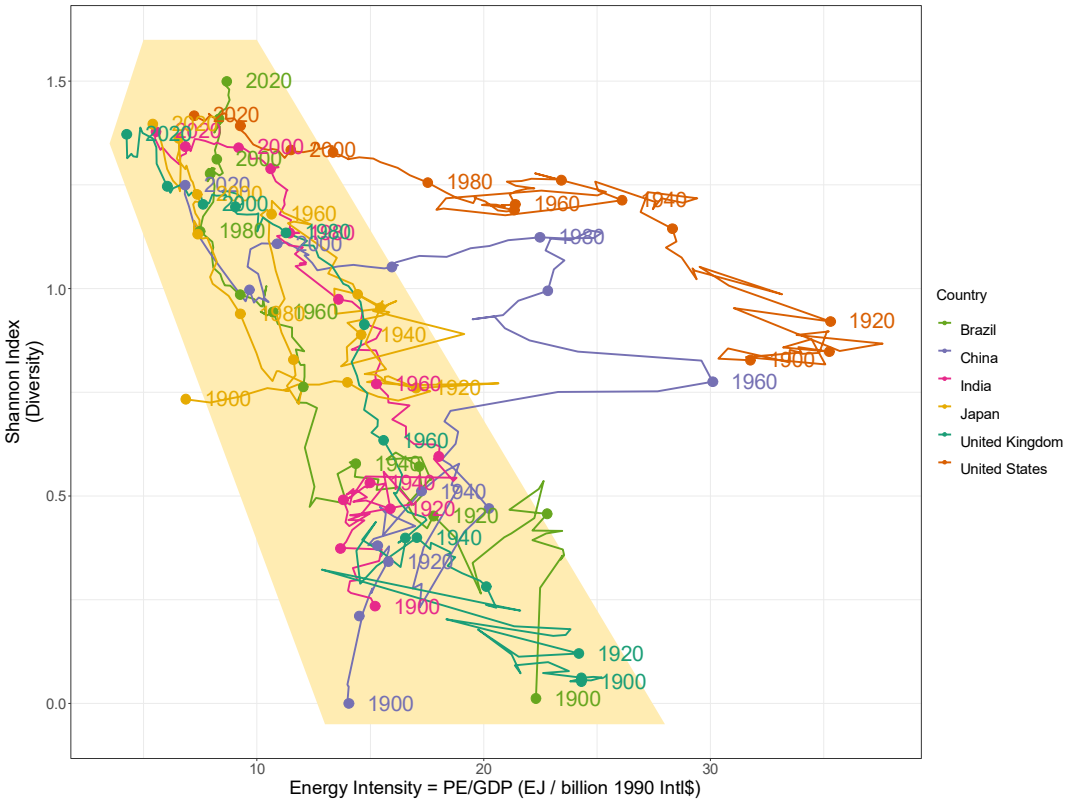


fig. S4. Policy effort equivalent to a 10% in primary energy reduction target. EJ in brackets, countries are ordered by size of energy system and split into net importers and net exporters. China, Nigeria, and Australia are not shown as their import diversification policy could not reach the 10% Primary Energy reduction target. See box S6 for more details.

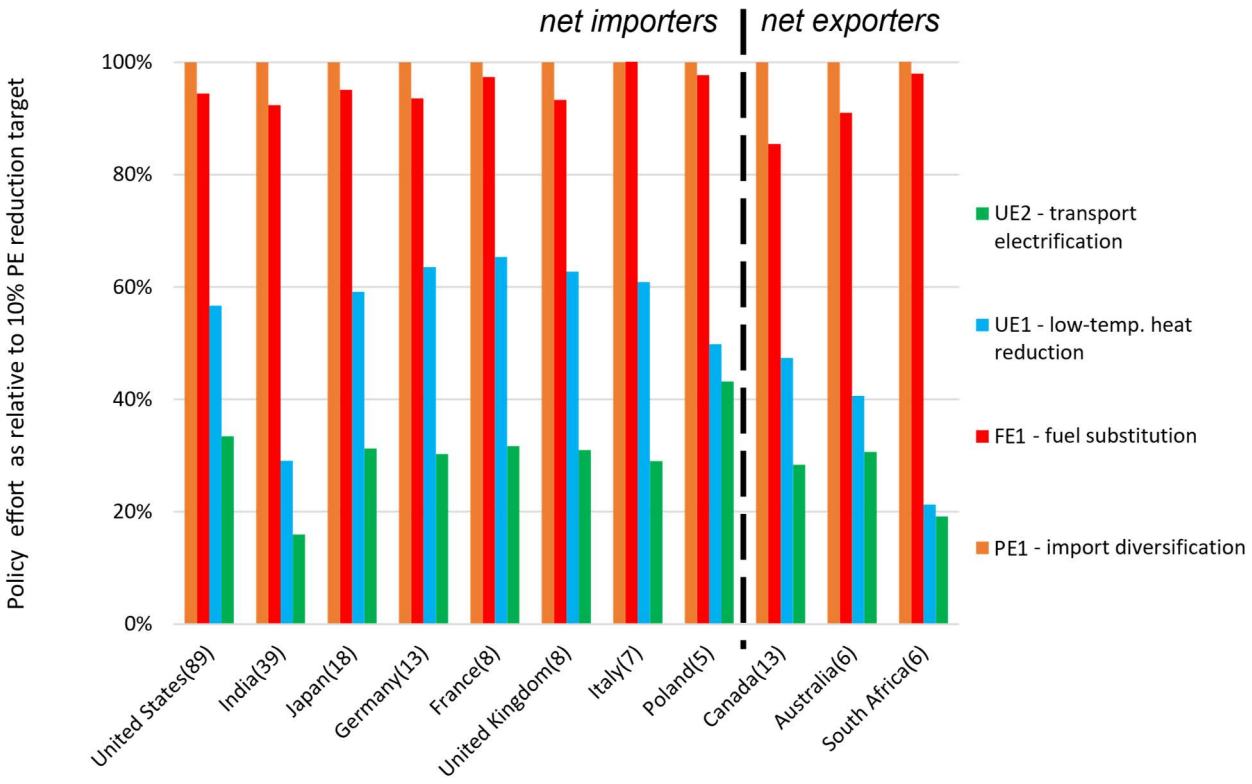
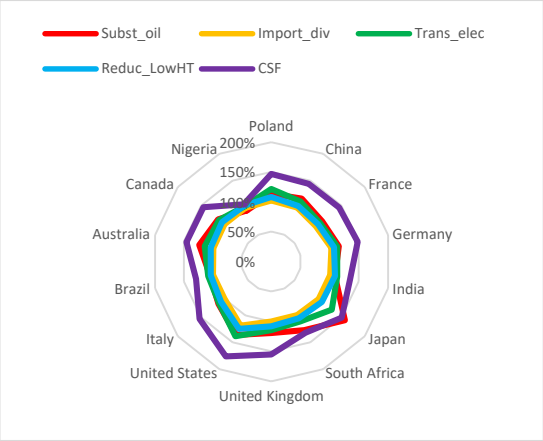


fig. S5. Effects of policy interventions in improving the energy security indicators: average of all indicators and by country. CSF means critical social functions. See more details in the spreadsheet "Summary".

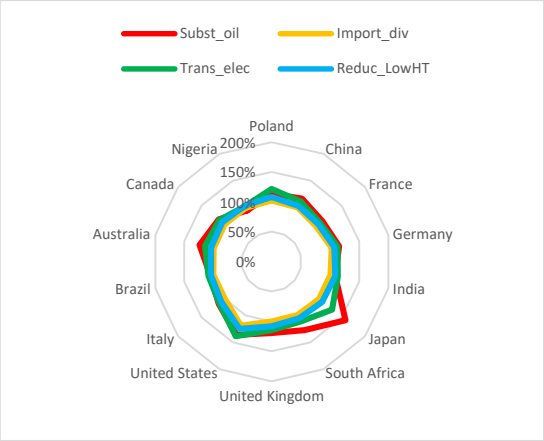
Average of all indicators

<u>ALL ANALYZED COUNTRIES</u>

With CSF



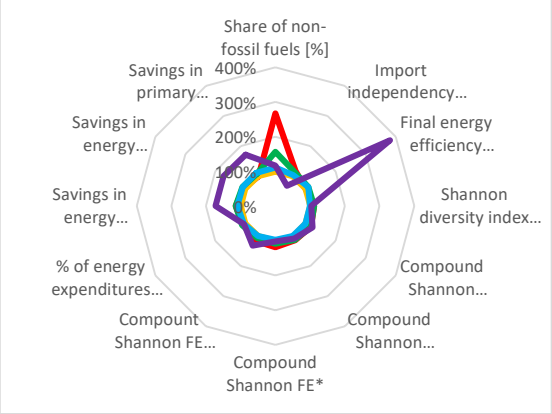
Without CSF



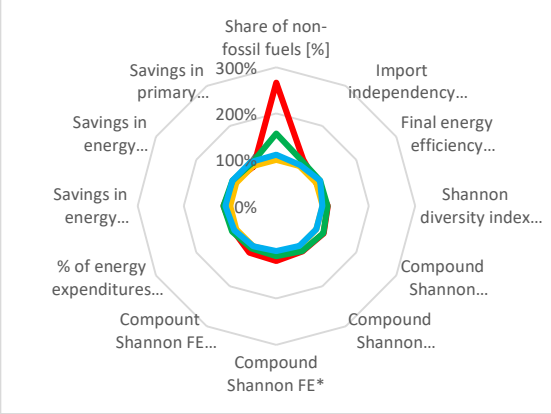
Values of all indicators

<u>AUSTRALIA</u>

With CSF

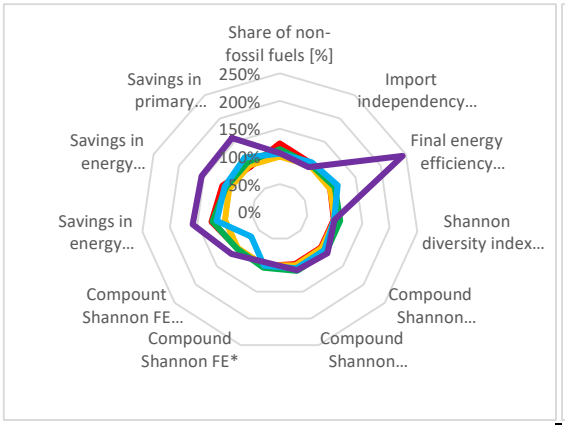


Without CSF

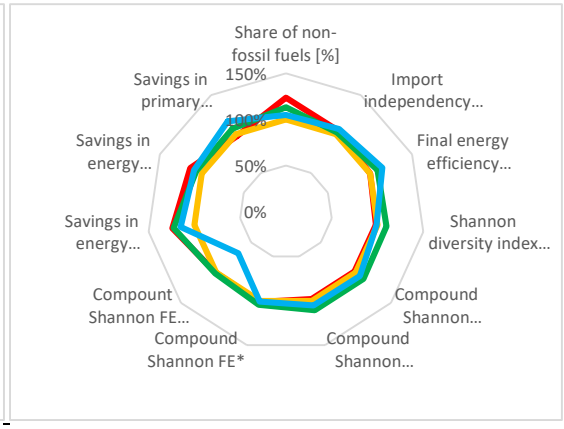


BRAZIL

With CSF

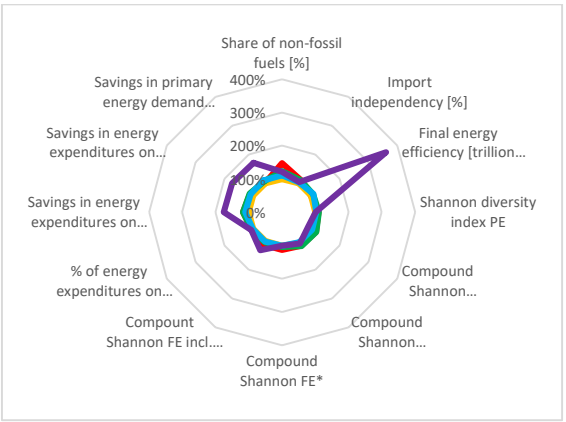


Without CSF

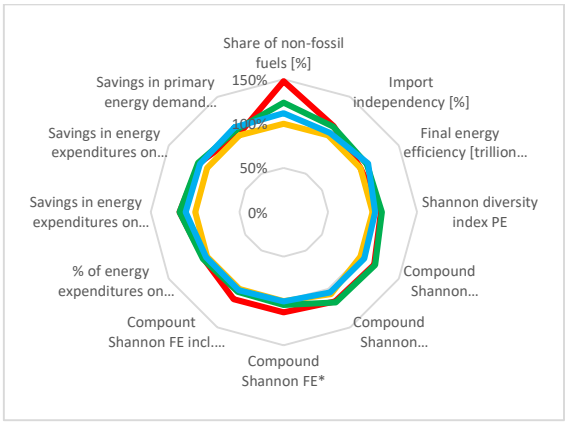


CANADA

With CSF

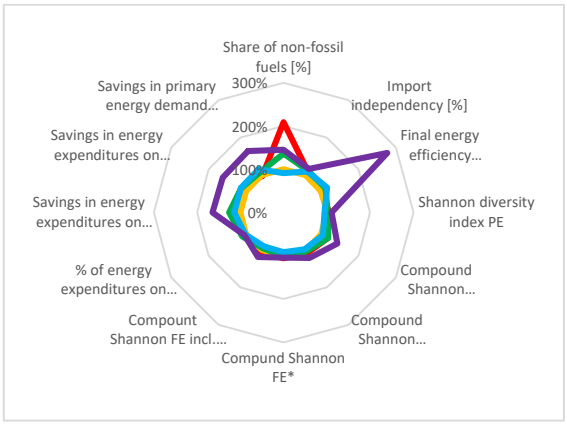


Without CSF

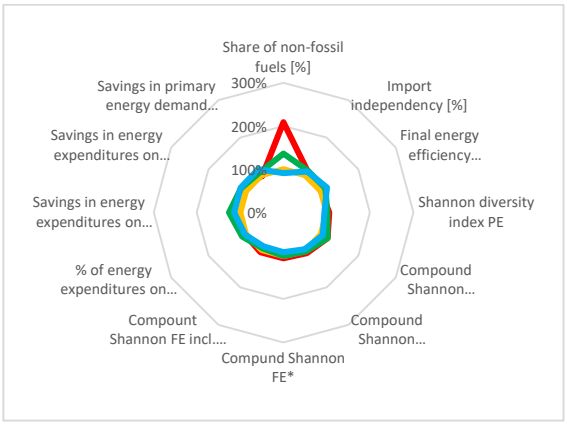


CHINA

With CSF

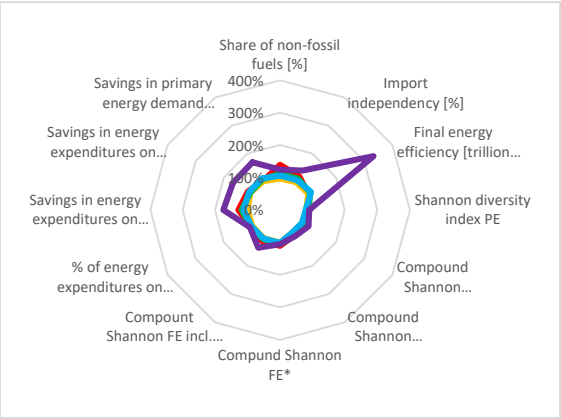


Without CSF

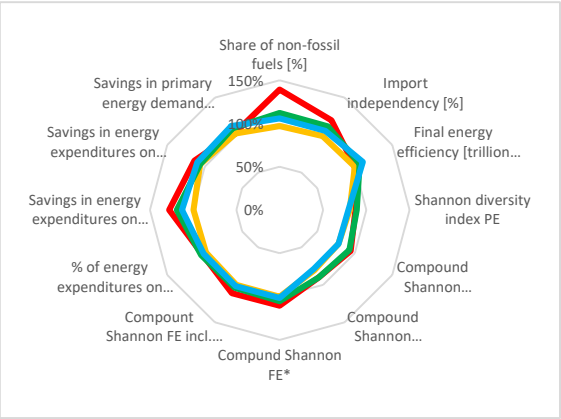


FRANCE

With CSF

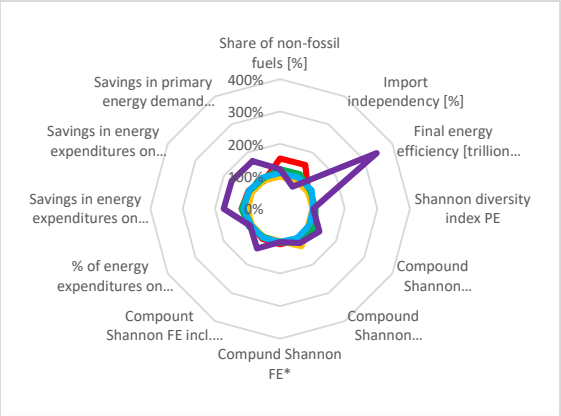


Without CSF

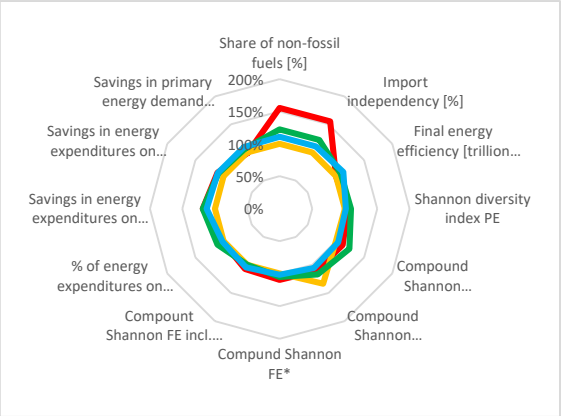


GERMANY

With CSF

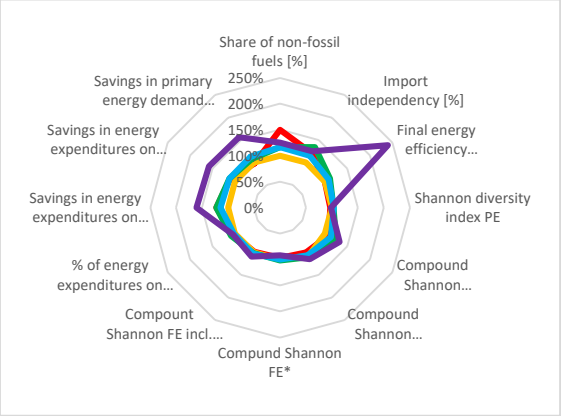


Without CSF

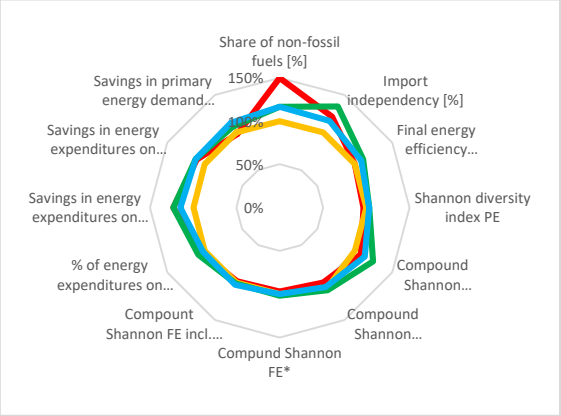


INDIA

With CSF



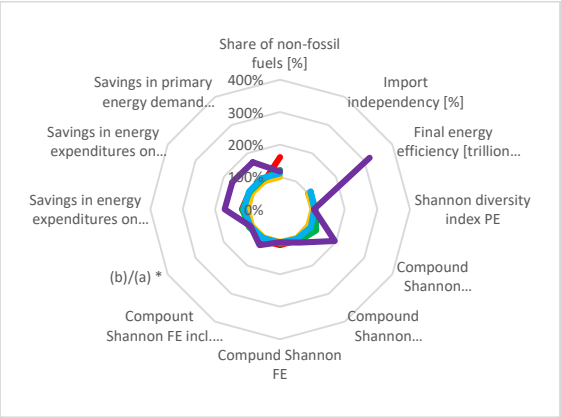
Without CSF



ITALY*

(import independency being 0, no improvement rates are possible to calculate.)*

With CSF



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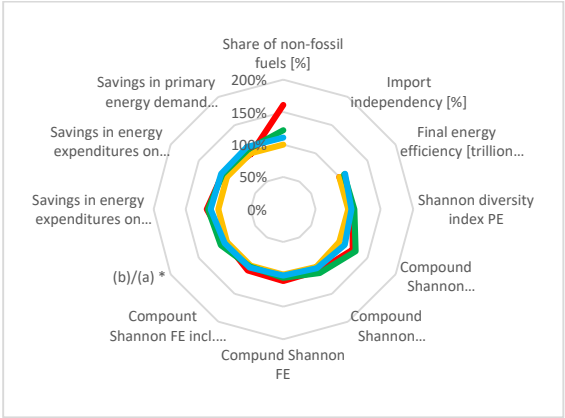
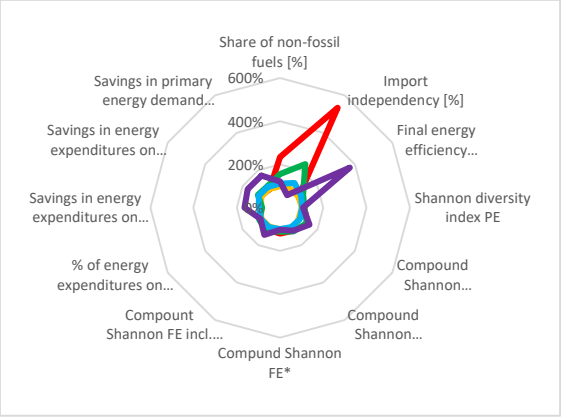


JAPAN

With CSF



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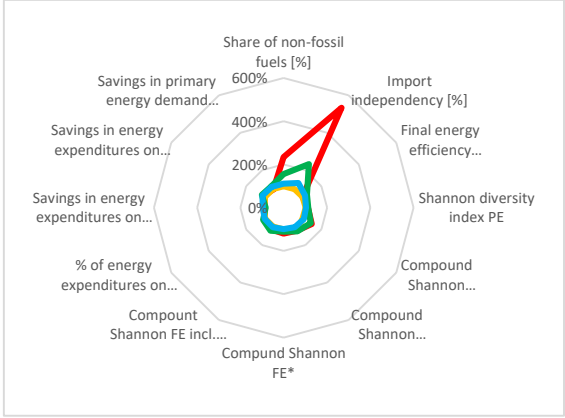
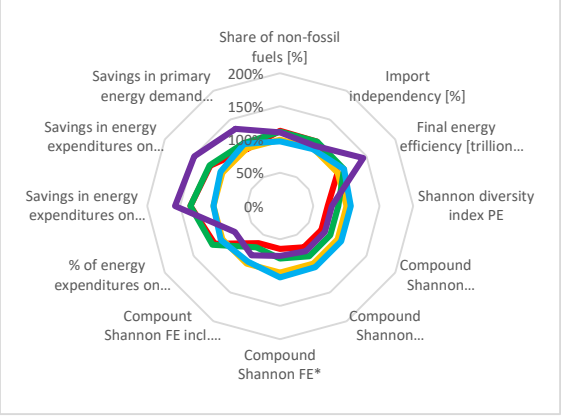


NIGERIA

With CSF



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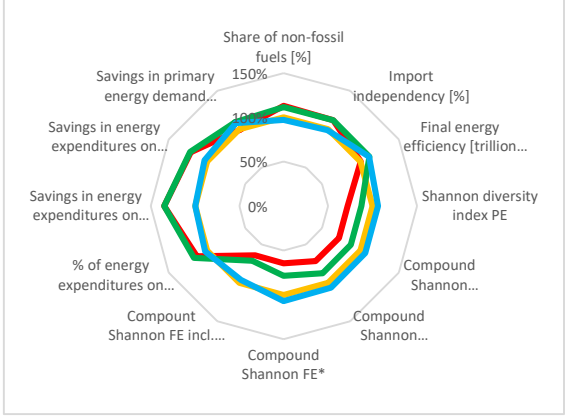
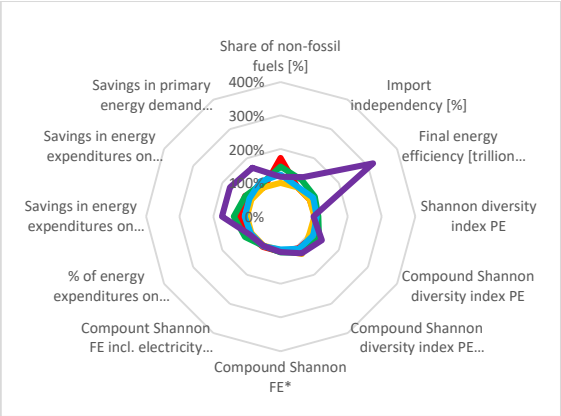


POLAND

With CSF



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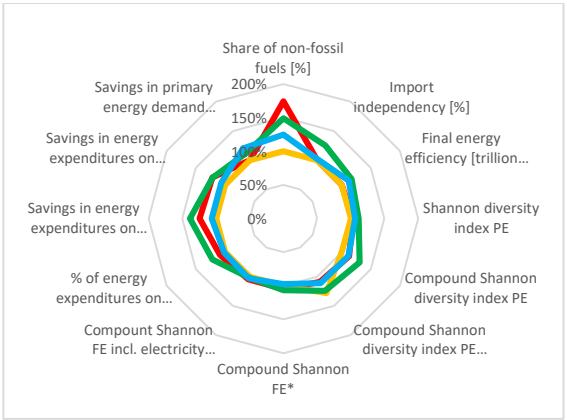
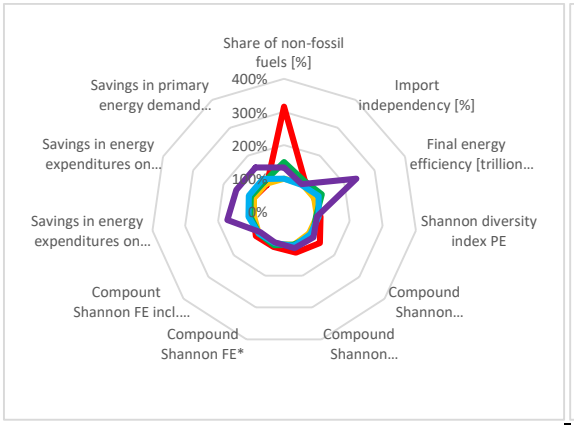


SOUTH AFRICA

With CSF



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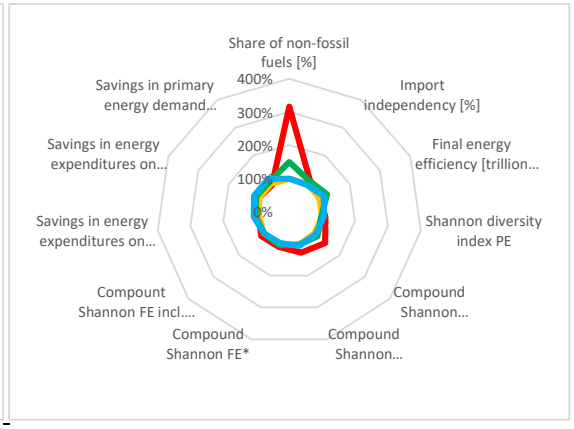
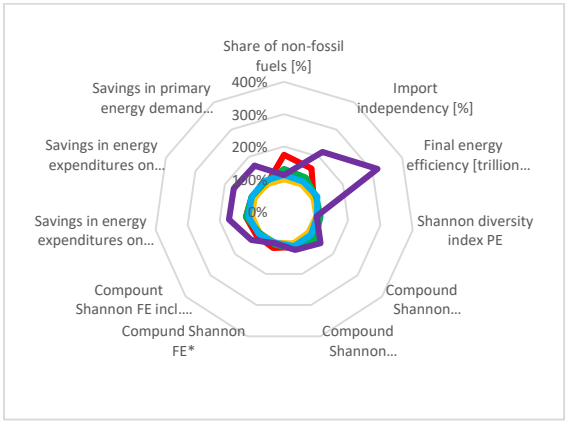


UNITED KINGDOM

With CSF



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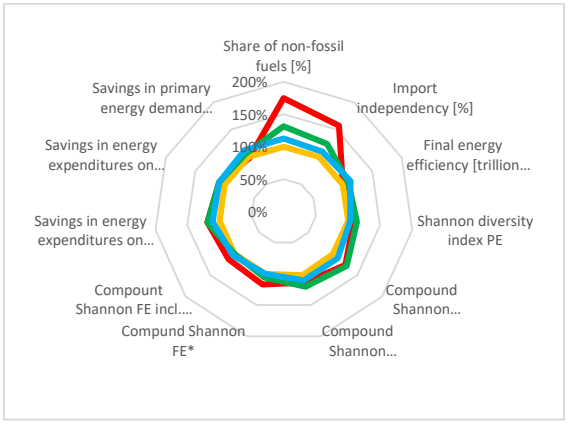
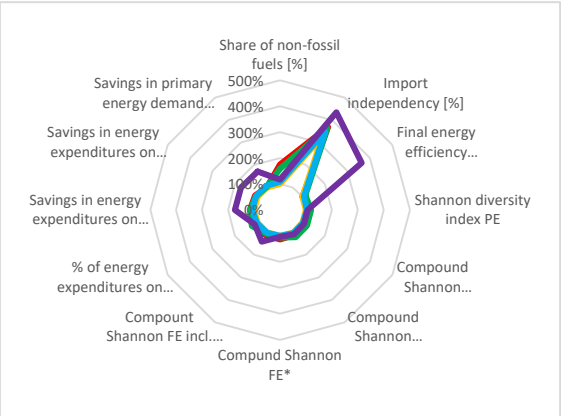


UNITED STATES

With CSF



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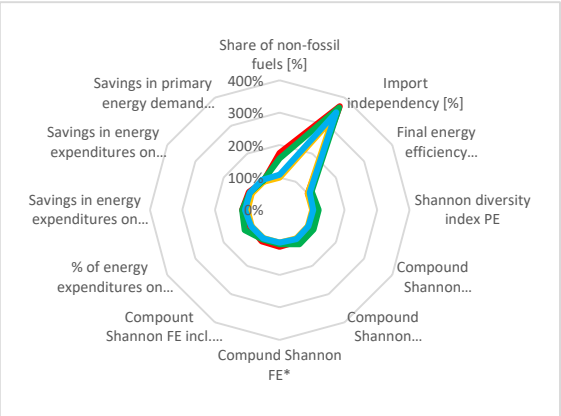
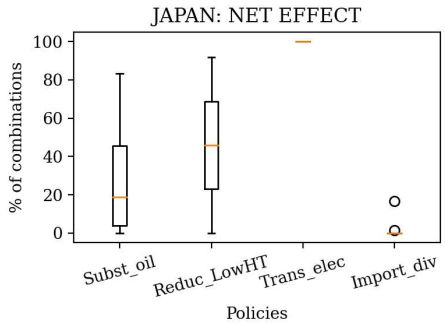
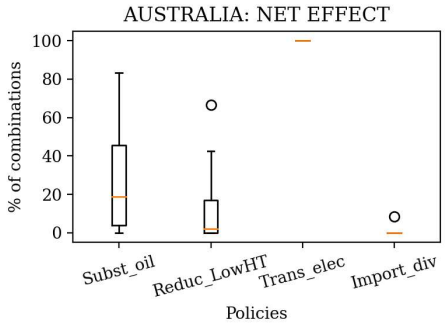


fig. S6. Sensitivity analysis: Box plot comparison of policy interventions for representative developed (OECD) vs developing (Non-OECD) countries and energy importers vs exporters. Average and range of times that each policy interventions ranks first in the combinations of the 12 indicators by n = 1,…, 12 group of indicators.

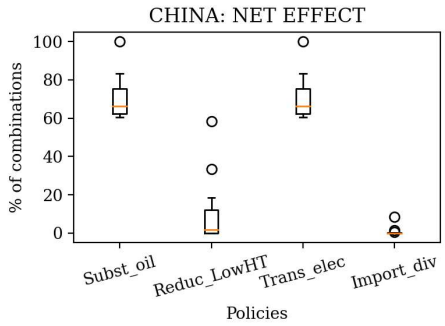
Energy importer | Energy exporter

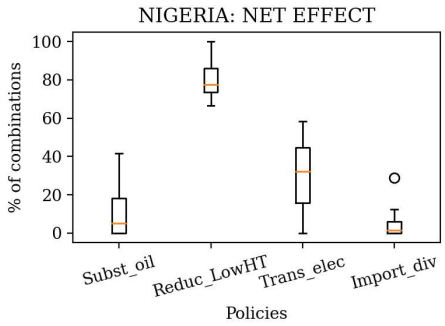
OECD





NON-OECD





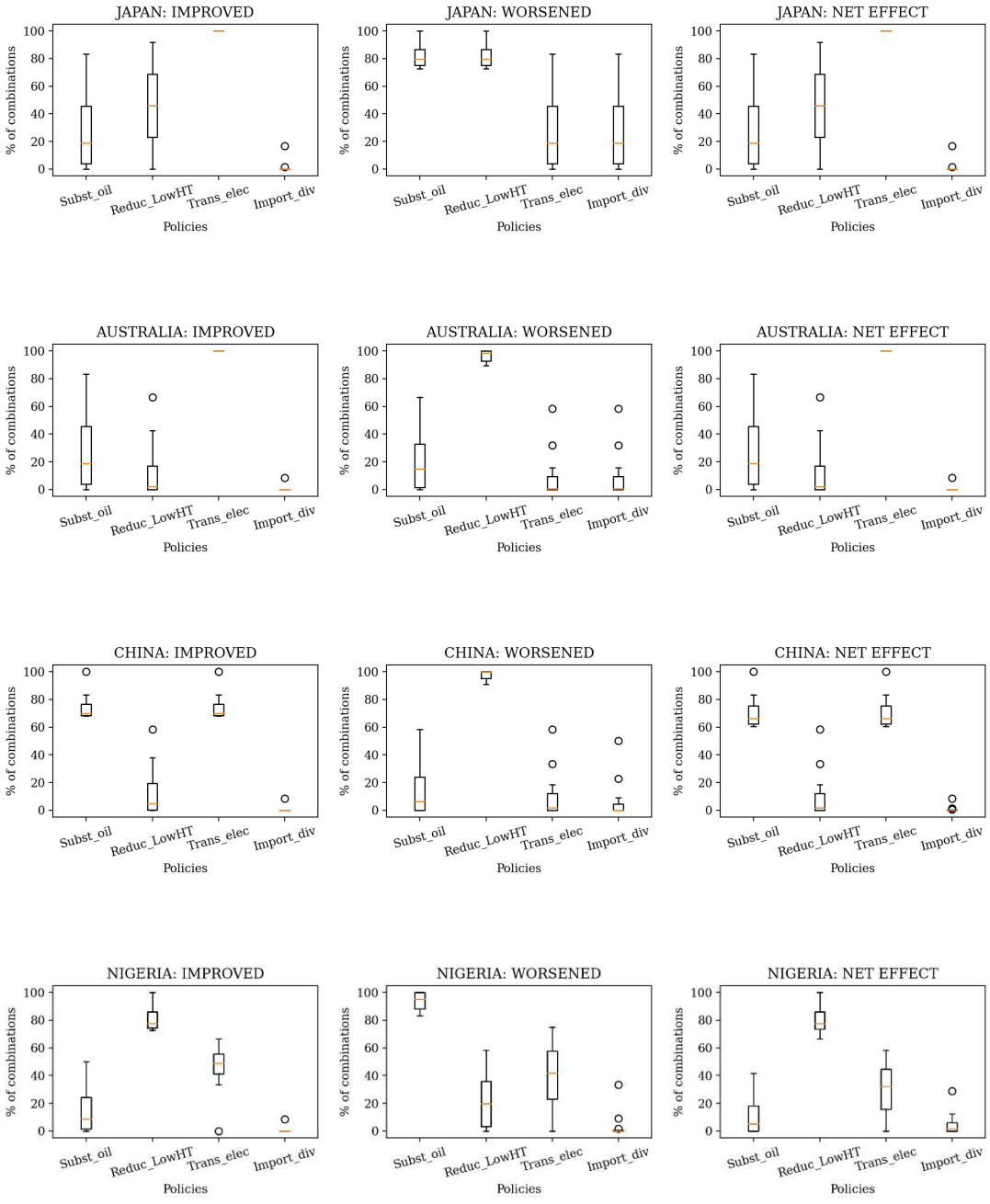

JAPAN: IMPROVED
JAPAN: WORSENED
JAPAN: NET EFFECT
AUSTRALIA: IMPROVED
AUSTRALIA: WORSENED
AUSTRALIA: NET EFFECT
CHINA: IMPROVED
CHINA: WORSENED
CHINA: NET EFFECT
NIGERIA: IMPROVED
NIGERIA: WORSENED
NIGERIA: NET EFFECT
% of combinations
0
20
40
60
80
100
Subst_oil
Reduc_LowHT
Trans_elec
Import_div
Policies

fig. S7. Best policies interventions according to the different combinations possible of the 12 indicators available in sub-sets of n=1,…, 12 elements, for all 14 countries surveyed. See more details in the Script in attachments.

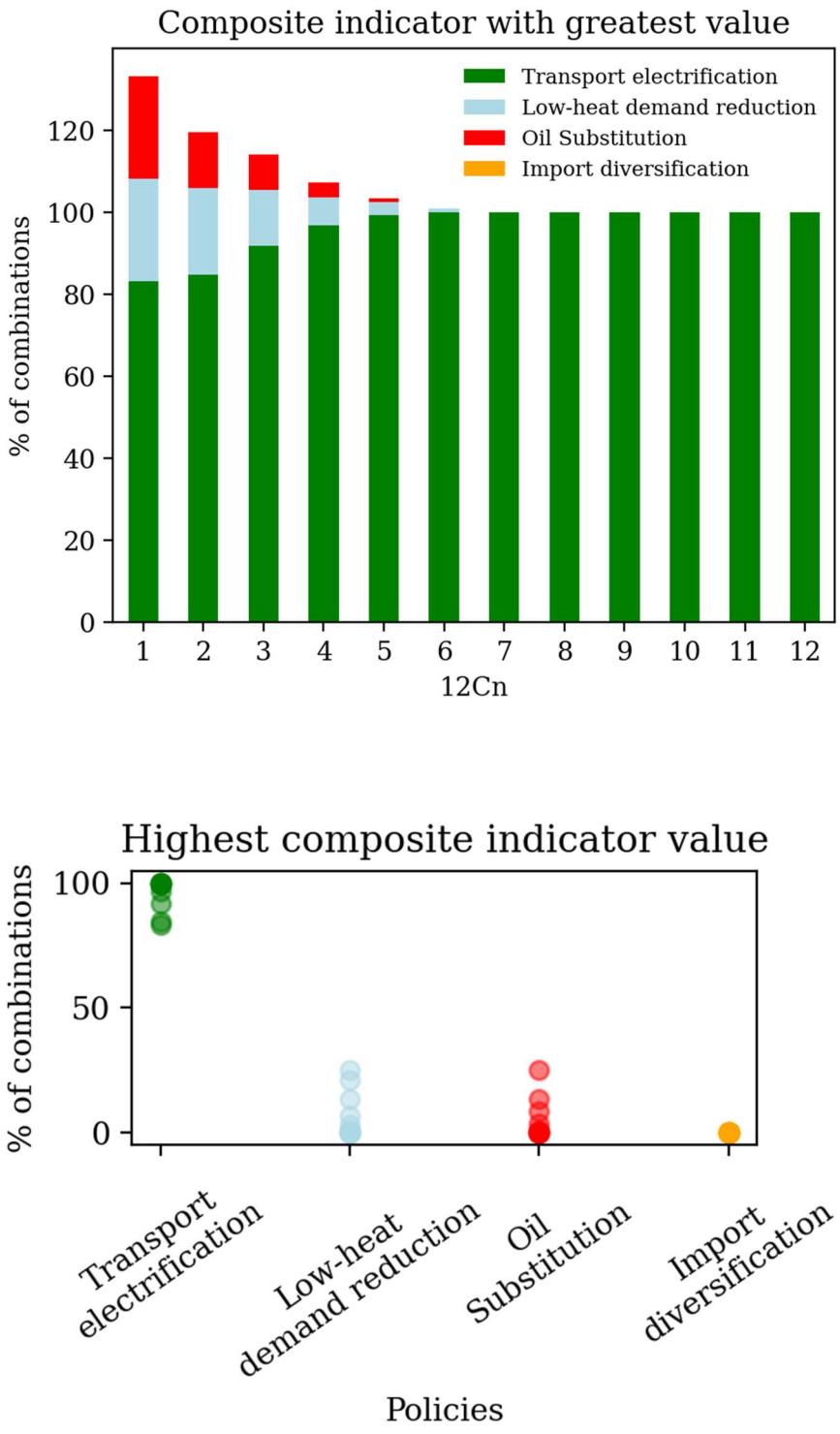
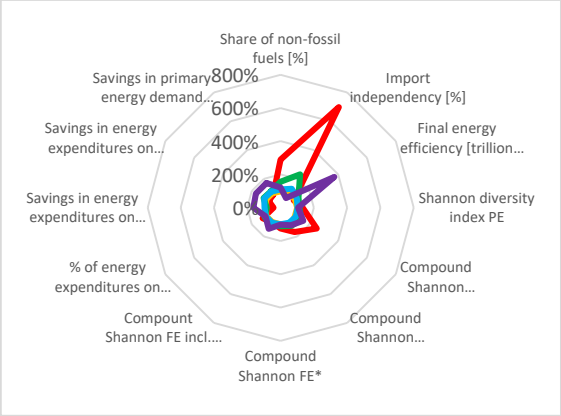


fig. S8. Comparison of alternative policies for Japan. Hydrogen production for fuel substitution and heat pumps deployment to increase efficiency in low-temperature heat. Labels are the same as in fig. S4. See more details in the spreadsheet “Summary”.

Fuel substitution with hydrogen production

With CSF



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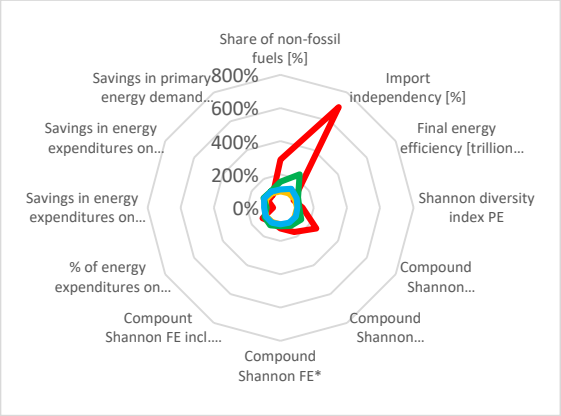
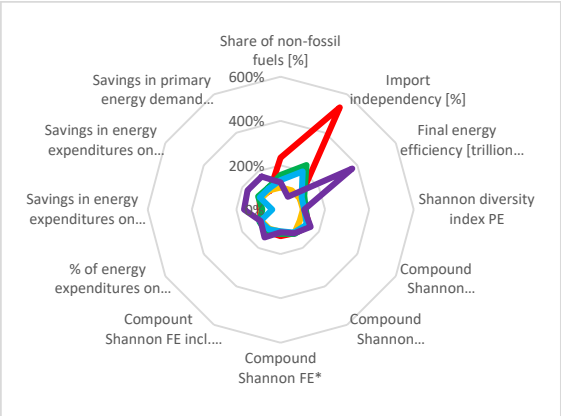


Low-temperature heat reduction with heat pumps

With CSF



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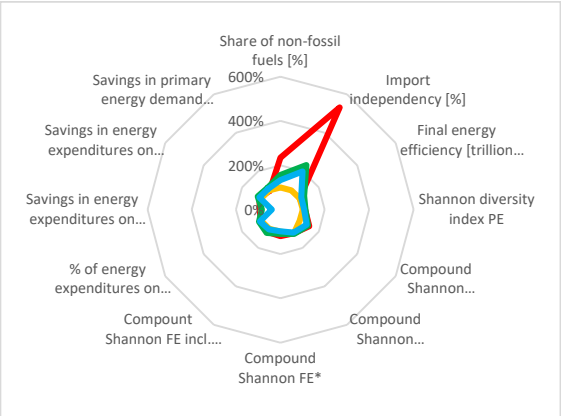
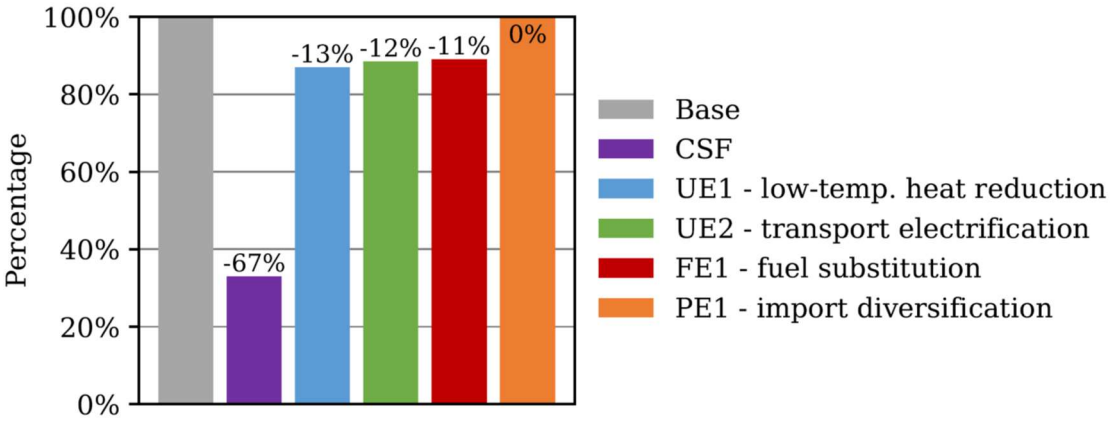


fig. S9. Impact of the policy interventions on reducing CO2 emissions relative to Base (100%).
See more details in the spreadsheet “Summary”, in the sheet “emissions.”



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Paper 1: Balancing Energy Transition: Assessing Decent Living Standards and Future Energy Demand in the Global South

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Abstract: Achieving low energy demand in buildings is crucial in climate change mitigation pathways. In the Global South, however, reducing the energy demand blanketly is not advisable due to critical gaps in access to the basic services supporting Decent Living Standards (DLS) and well-being. Current energy demand scenarios for the building sector mostly overlook achievement of DLS. Thus, data availability gaps and model limitations in representing distributional aspects hinder modelling future energy demands to meet DLS in the Global South. Supported by new evidence from a set of detailed sectoral and integrated assessment models, this research contributes to bridging this gap by exploring future trends in DLS achievement and linkages with energy demand in the Global South, focusing on the residential sector in India. We consider four key dimensions of DLS: sufficient space and durable housing, thermal comfort, access to basic appliances and to clean cooking. We show that the substantial increase in residential floor area, especially in urban areas, will not guarantee an improvement in DLS levels due to continuing non-durable housing construction. Despite an increase in space cooling demand of almost 400-800% by 2050, only 15% of the population will have access to residential air conditioning, mostly in urban buildings. In contrast, access to clean cooking will increase to almost 80% under current policies, with an energy demand increase of only around 8% by 2050 due to energy efficiency improvements.

Paper 2: High well-being with low energy consumption: scenarios for residential India

Alessio Mastrucci[1], Souran Chatterjee[2], Kaveri Ashok[3], Vassilis Daioglou[4,5], Srihari Dukkipati[6], Oreane Edelenbosch[5], Sarah Khan[3], Poornima Kumar[7], Ashok Sreenivas[6], Diana Ürge-Vorsatz[8], Victhalia Zapata[5], Shonali Pachauri[1]

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Abstract: The Global South is facing unique challenges in pursuing climate and sustainability goals. On one hand, energy demand is continuously growing to unprecedented levels, on the other hand there are still large gaps in access to decent living standards (DLS). The provision of improved access to DLS will require additional energy demand and emissions. However, the amount of energy demand for DLS and potential impact of demand-side mitigation strategies are still unclear. Here, we run a multi-model study to investigate the effects of simultaneously providing broader access DLS and implementing energy efficiency measures on energy demand and CO2 emissions under current and stringent climate policies. We focus on the residential sector in India, being the country with the largest population in the world but significant development needs. The results of this study show that providing broader access to DLS will require a substantial amount of additional energy, particularly for cooling and appliances, for bridging the gaps especially among low income and rural households. The implementation of energy efficiency improvements using available technologies can contribute to greatly reduce the energy demand and emissions. Under stringent climate policies, the provision of DLS combined with demand- and supply-side measures only marginally increases CO2 emissions, contributing to support the well-being of populations while not compromising the achievement of ambitious climate targets.

PATHWAYS TO ACHIEVE NET-ZERO AND ENERGY INDEPENDENCE TRANSITION IN THE EU BUILDING SECTOR

Diána Ürge-Vorsatz1, Souran Chatterjee1,2

1. CENTRAL EUROPEAN UNIVERSITY, 2. UNIVERSITY OF PLYMOUTH Quellenstr. 51 Room A 609 1100 Wien Austria

Executive summary

The potential for transforming the buildings sector holds immense promise in mitigating the adverse effects of climate change, thereby assuming a pivotal role in achieving the objectives outlined in the Paris Agreement. However, empirical analyses within the literature that offer comprehensive insights into the future trajectories of both residential and commercial building sector transformations remain scarce, resulting in uncertainties surrounding policy decisions. In this study, we utilize our High-efficiency Building (HEB) energy model to present future outlooks on enhancing building energy efficiency, disaggregated across each of the European Union (EU) member states. We present four distinct scenarios, each reflecting varying degrees of commitment from EU member states towards implementing energy efficiency measures, aiming to shed light on the potential consequences of current policy decisions by the year 2060. Our modeling findings indicate that augmenting energy efficiency in the buildings sector through accelerated rates of EU-wide building renovations (retrofitting) and the construction of new advanced buildings not only holds unprecedented potential for reducing energy demand but also facilitates progress towards achieving climate neutrality objectives in the ensuing century. The total final energy demand which is the summation of space heating, space cooling and hot water energy demand, can be reduced by 83% if best building practises are implemented compared to 2022. Along with the best building practises, if onsite solar energy production potential is considered, then even more reduction can be achieved (97 % compared to 2022). However, if the EU member states does not adhere to the existing efficiency standards, then it leads to 7% increase in total final energy demand until 2060, while the present efficiency rate shows a 73% decrease in final energy demand until 2060.

Results from the key EU MS indicate that a significant reduction in final energy demand can be achieved if the best building practises are followed. For instance, Germany (85%), Belgium (85%), France (83%), and the UK (83%) show potential reductions until 2060. However, the reduction is comparatively lower in Spain (71%) and Portugal (68%) when compared to 2022 values. Conversely, if the present efficiency rate is not followed in these member states, then there is an observable increasing trend in energy demand across the key regions. The findings from the “Frozen Efficiency scenario” underscore the importance of implementing more ambitious energy efficiency policies. Without such policies, due to the growth in EU floor area, future building energy demand is projected to increase. Furthermore, the scenario analysis suggests that without the adoption of best building practices, with existing energy policies, the EU region risks locking in only 24% of energy demand reduction potential by 2060 compared to 2022. Additionally, findings from the “Towards Net-zero” scenario indicate that EU countries can potentially reduce their energy demand for three key end-uses — space heating, space cooling, and hot water — to almost zero by 2060.

Furthermore, the findings of this study reveal that EU member states could significantly reduce their reliance on imported natural gas by 2050 through energy savings resulting from enhanced building efficiency. While Latvia, Estonia, Finland, and Slovakia may still depend partially on Russian gas imports, other countries could achieve reduced import dependence as early as 2035, with Romania being one of them.

Furthermore, retrofitting net-zero energy buildings has the potential to greatly diminish the EU's dependence on non-EU natural gas imports by 95%. Our advanced building energy model indicates that implementing current best practices in the building sector could lead to a substantial reduction in EU natural gas imports by 2050. Therefore, prioritizing energy efficiency should be a key aspect of the EU's response to current energy-related crises. This includes mitigating the impact of fossil fuel-related sanctions and rising energy prices, which can also significantly contribute to emissions

reduction, alleviate the cost-of-living crisis, address insufficient winter heating levels, combat fuel poverty in the long term, and enhance indoor and outdoor air quality, consequently improving overall health and productivity.

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

EDIT Project Report

Analyzing Low Energy Demand Scenarios: CGE and Index Decomposition with Climate Change Impact Assessment

February 2024

Tae Yong Jung

Korea International Economic Association

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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

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.

- EDITS Project Team (Korea)
  - Tae Yong Jung (Project Manager, Professor, Yonsei University)
  - Yong Gun Kim (Senior Fellow, Korea Environment Institute)
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2. Impacts of Climate-induced Energy Demand Change and the Economic Impacts of Low Energy Demand Scenarios

2.1. Introduction

There is increasing attention to low-energy demand scenarios globally, and the NGFS (Network for Greening Financial System) identified the Low Demand scenario as one of the orderly transition scenarios. Particularly, the NGFS Scenario emphasized the Low Demand Scenario can lead to the smallest exposure to transition and physical risks. This indicates the necessity of further exploration of the economic impacts of low-energy demand scenarios.

In addition, as the global temperature continues to increase, the global temperature recorded nearly 1.5 degree-Celsius above the pre-industrial level in 2023 (Copernicus Climate Change Service, 2024). It is expected to become higher in 2024 and become over 1.5-degree above the pre-industrial level. In this sense, global warming can affect the cooling and heating demands globally, and this can affect the achievement of low-energy demand in the future. Thus, it is necessary to understand not only the impacts of global temperature change on cooling and heating energy consumption but also the economic impacts of low energy demand scenarios with consideration of the climate-induced energy demand changes.

2.2. Literature Review

Numerous research efforts have explored methods and pathways to reduce energy demand. Low Energy Demand (LED) scenarios, in general, rely on measures and strategies that significantly lower energy use. Gaur et al. (2022) identify the key factors for low energy demand scenarios, and those key factors are technology, economic system, behavioral and lifestyle changes, and policy measures.

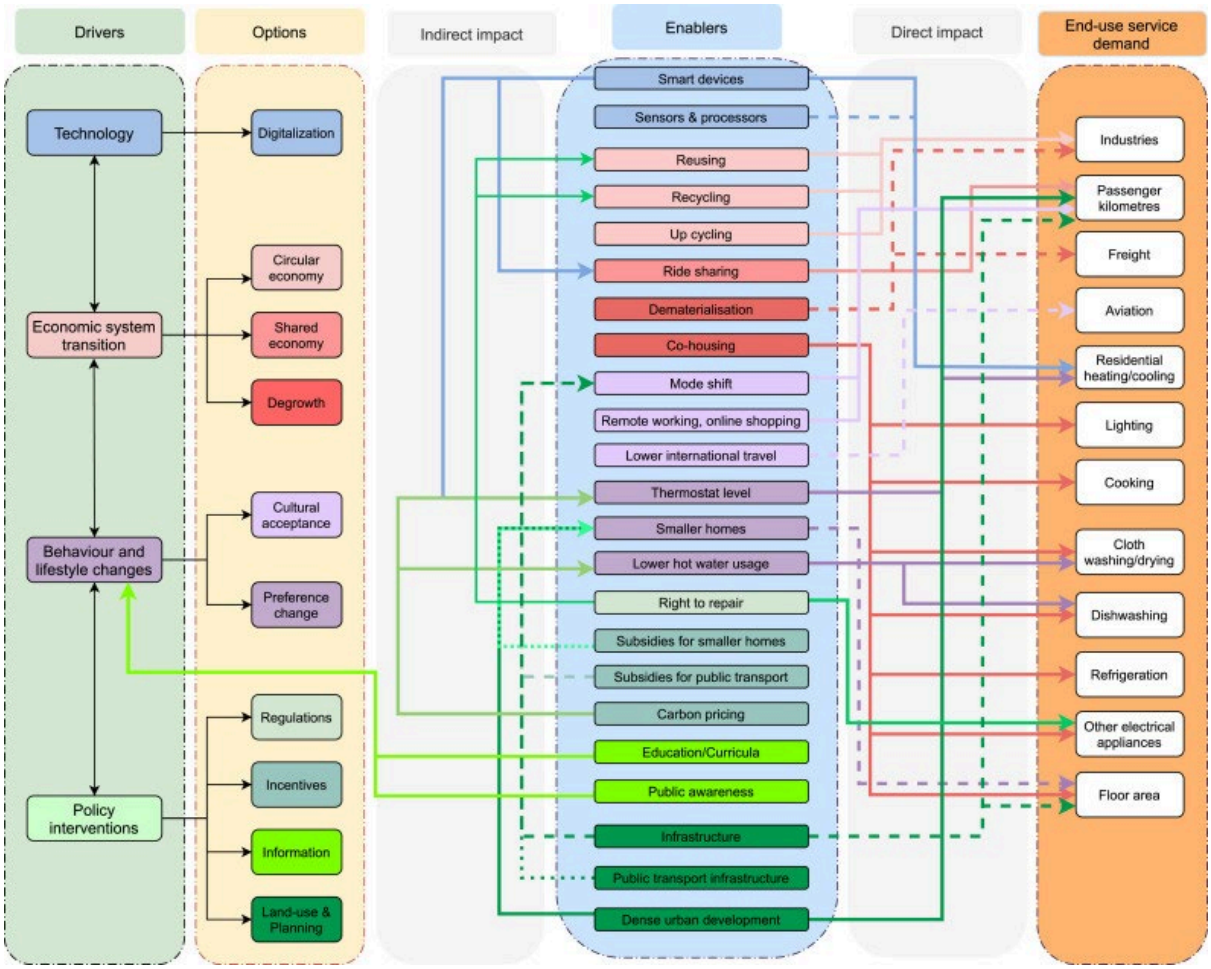


Figure 1. Interactions among drivers, enablers, and end-use services

Gaur et al. (2022) study the Irish Low Energy Demand approach by using the TIMES-Ireland Model (TIM). The study establishes the Low Energy Demand scenario for Ireland, and it includes the assumptions for reducing energy demands in four sectors, which are transport, residential, industry, and services.

Napp et al. (2019) focus on technology's role in the decarbonization of the energy system. The objectives of the study are (i) how utilizing cutting-edge technologies and reducing energy consumption support the challenging sectors' decarbonization and emissions reductions and (ii) the implications of achieving decarbonization goals and reducing the dependence on BECCS (Bioenergy with Carbon Capture and Storage). This study utilized the TIAM-Grantham model developed by the Energy Technology Systems Analysis Programme (ETSAP). This model covers the entire energy supply chain from the extraction of energy resources to the final end-use energy services, such as heating, lighting, or mobility. For future energy service demands, the model considers exogenous inputs, including GDP, population, household size, and the share of each sector. Also, the model considers energy system data, including

technology costs, resource availability, and supply curves. The results of the study emphasized that advanced low-carbon technologies can reduce the residual emissions in transport and industrial sectors and stressed the importance of advanced technologies in challenging sectors. Also, the study emphasized the importance of significant behavioral changes in reducing energy demand in end-use sectors. Lastly, the study emphasized the necessity of high carbon prices for achieving an ambitious carbon budget and highlighted the need for policy support to encourage technological innovation and demand reductions.

Low Energy Demand scenarios are hard to define since energy demands are affected by many different factors, such as human lifestyles, efficiency of appliances, production technologies, industry structures, and economic growth. For most of these driving factors, technology plays a key role. According to Blanco et al.(2022), technological innovation can bring about new and improved ways of delivering services that are essential to human well-being. At the same time as delivering benefits, innovation can result in trade-offs that undermine both progress on mitigation and progress towards other Sustainable Development Goals (SDGs). Trade-offs include negative externalities – for instance, greater environmental pollution and social inequalities – rebound effects leading to lower net emission reductions or even increases in emissions, and increased dependency on foreign knowledge and providers.

By disaggregating the two different kinds of demands, final demands and intermediate demands, LED scenarios can be understood as lower energy in the two different sectors: final demand (household and government sector) and intermediate demand (industry sector). Regarding the final demand sector, low energy demand may be driven by changes in lifestyles and consumption behavior (including the purchase of green cars), and higher efficiencies of appliances, while that in the industry sector might be led by efficiency improvements, eco-design, etc. Most low-carbon technologies play an important role in LED scenarios, with the exception of renewable energies, nuclear, and CCS technologies, which are supply-side mitigation technologies.

Gaur et al. (2022) develop the Irish Low Energy Demand (ILED) mitigation narrative and applies the TIMES-Ireland model, an energy systems optimization model, where Energy Service Demands are decoupled from economic growth by shifting travel, increasing end-use efficiency, densifying urban settlement, focusing on low-energy

intensive economic activities and changing social infrastructure. Atit and Atsushi (2023) evaluate policies and measures on greenhouse gas (GHG) emissions mitigation to meet the target at the provincial level in Nakhon Ratchasima Province, Thailand.

Efficiency improvement has a huge potential to reduce energy consumption but also leads to the 'rebound effect'. The behavioral responses increase energy demand and reduce the potential energy savings, through various types of channels, including 'direct rebounds', 'indirect rebounds' and 'macroeconomic rebounds'. Barner et al. (2021) provide empirical evidence of an economy-wide rebound effect of 78% to 101% after two years in France, Germany, Italy, the U.K., and the U.S. This suggests that energy efficiency improvements alone may have a limited impact in reducing future energy use. Golnaz et al (2020) use a two-step procedure to measure both short and long-term energy rebound effects in the Swedish manufacturing industry, and they showed that partial rebound effects exist within most manufacturing sectors, meaning that the rebound effect decreased, but did not totally offset, the energy and emission savings expected from EEI. Yu et al. (2020) propose a method of identification and evaluation of equipment energy efficiency improvement policy (EEEIP), and the application is verified by analyzing the example of EEEIP in Japan (Top Runner policy, TRP). It shows that the policy has a good effect on tertiary industry and transportation, while the effect on residential is poor. For the life cycle, the TRP of air conditioning and passenger cars can bring better CO2 emission reduction effects, but the emission reduction effect of lighting is basically offset. Boehringer and Rivers (2018) develop a stylized general equilibrium model to decompose the rebound effect of energy efficiency improvements into its partial and general equilibrium components, including a composition channel, an energy price channel, a labor supply channel, and a growth channel. The paper discusses the rebound effect of energy efficiency improvements and identifies key drivers of the general equilibrium rebound effect. The total rebound effect in the US manufacturing sector is estimated to be 67%, with two-thirds occurring through the partial equilibrium rebound channel and one-third through the general equilibrium rebound channel.

Digital technologies can promote large increases in energy efficiency through coordination and an economic shift to services, but they can also greatly increase energy demand because of the energy used in digital devices. System-level rebound effects may also occur. (Blanco et al. (2022)) In the specific context of mobility,

residential buildings, and public infrastructure, digital technologies can contribute significantly to improving energy efficiency, particularly when integrated into existing systems. (IEA 2020) This integration can potentially result in a reduction of energy demand and the associated greenhouse gas emissions from buildings and industries while ensuring that service levels are maintained. Estimations suggest that energy savings of 5 to 10% can be achieved, with the possibility of even greater reductions. However, it is crucial to consider that the economic growth resulting from enhanced energy and labor productivity can also drive an increase in energy demand and the corresponding greenhouse gas emissions. (Lange et al. 2020) It is worth noting that the benefits of digitalization are not limited to energy efficiency alone, as it can also positively impact carbon-intensive technologies (Victor 2018).

NGFS (Network for Greening the Financial System) (NGFS, 2023) consists of a group of central banks and supervisors to analyze the impact of climate change on the economy and financial system. In order to do so, NGFS develops different transition scenarios and utilizes three globally well-known Integrated Assessment Models, such as REMIND-MAgPIE from the Potsdam Institute for Climate Impact Research, GCAM from the Pacific Northwest National Laboratory, and MESSAGEix-GLOBIOM from International Institute for Applied Systems Analysis (IIASA).

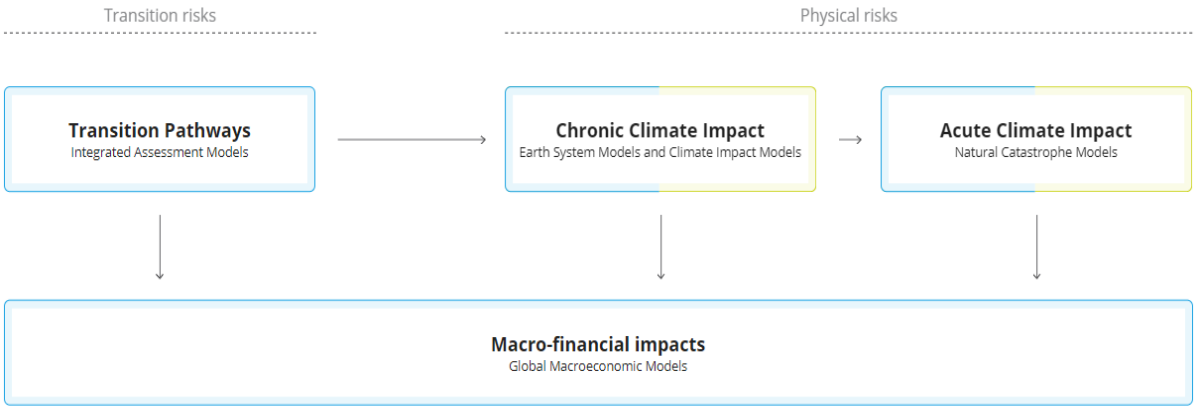


Figure 2. NGFS Scenario Analysis (Transition and Physical Risk) (Source: NGFS, 2023)

NGFS currently establishes 7 different pathways. In the latest Phase IV, NGFS developed two different pathways, and one of them is the ‘Low Demand’ scenario. This scenario is located in the third quadrant and indicates the lowest physical and transition risks compared to the other scenarios. This scenario includes additional

demand reductions in end-use sectors led by various approaches, including behavioral change and electrification. This new scenario indicates the potential of demand-side approaches in achieving Net Zero.

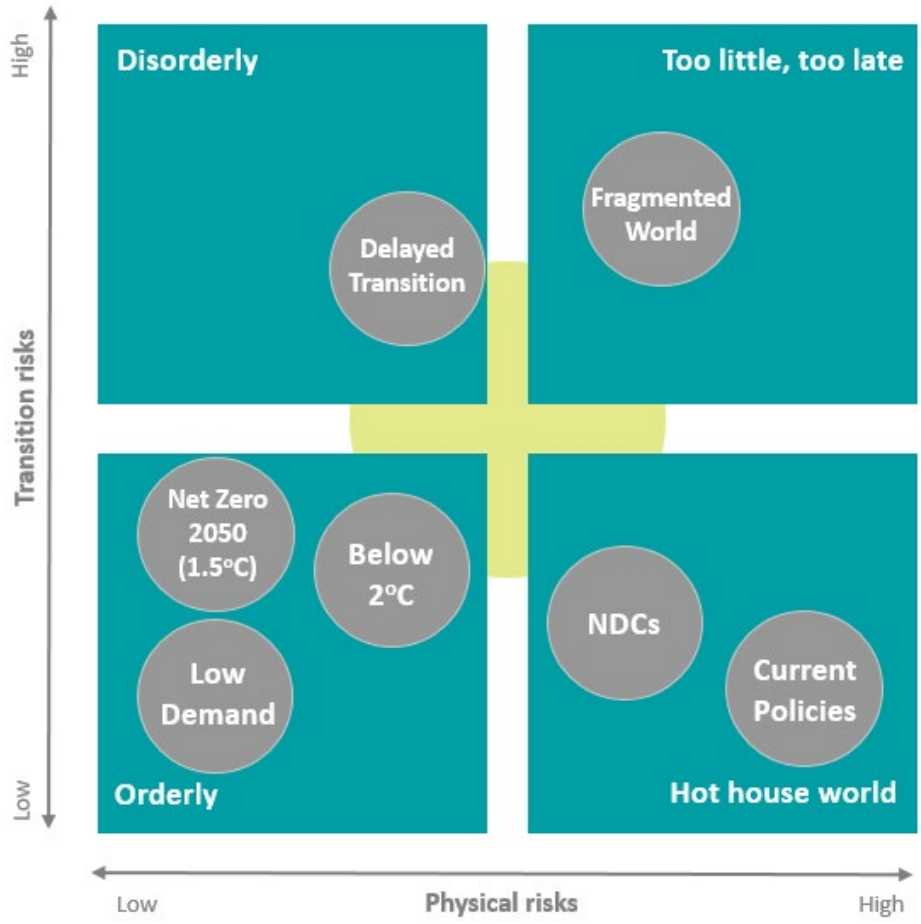


Figure 3. Four Quadrants and NGFS transition scenarios (Source: NGFS, 2023)

The characteristics of a low-demand scenario include measures for reducing energy demand and accelerating behavioral changes, which support the achievement of net zero transition and the 1.5-degree target. The modeling practices and analysis are developed based on the Shared Socioeconomic Pathway 2 scenario, but they additionally considered COVID-19 impacts on the economy and the final energy demand.

Semieniuk et al. (2021) discuss the challenges of simultaneously achieving reduced energy consumption and economic development in the context of global efforts to reach the 1.5-degree target. The IPCC scenarios rely heavily on substantial gains in

energy efficiency to support the growth, suggesting an unconventional trend of strong economic development alongside significant reductions in energy use, a notion that contracts the traditional linkage between energy consumption and economic growth. Semieniuk et al. (2021) argue that a faster transition to a low-carbon energy supply would be more practical compared to solely focusing on energy demand reductions. Also, the study emphasized the importance of an integrated approach to designing energy and economic policies that are both effective and sustainable, addressing the intertwined issues of energy strategy, economic growth, and climate change mitigation. It emphasized the inconsistencies in the assumptions of the scenarios. For instance, the decoupling between economic development and energy consumption in some regions is not consistent with the historical evidence. Also, the scenarios often anticipate the reductions in per capita final energy consumption to levels lower than those deemed essential for a decent living standard. Moreover, the ambitions for decoupling economic growth and energy consumption may contrast the future GDP projections and per capita energy consumption in historical data. In other words, it requires an unprecedented reduction in per capita final energy consumption and a significant transition from historical patterns. This study implies that the low-demand scenario analysis requires establishing a more balanced approach, not only focusing on demand-side options but also encouraging innovative low-carbon technology options.

In Low Energy Demand analysis, the impacts of climate change are often not included, but the global temperature rise would affect energy consumption, particularly of cooling and heating energy demand. Li et al. (2021) reviewed the literature on the effects of climate change on energy consumption in building heating and cooling. This study reviewed different methods of analyzing the effects of climate change on cooling and heating demands, and the methods included Statistical Methods, Model methods, and a combination of two methods. In many studies, degree day methods (cooling and heating degree day) are commonly used because of their simple, efficient, and reliable characteristics. The study identified that a large number of previous studies used the degree days calculated based on the daily temperature and ignored various characteristics, such as relative humidity and radiation. Also, the study indicated that climate change impacts not only the energy consumption for heating and cooling in buildings but also leads to a cascade of other issues, including the emission of carbon dioxide and various air pollutants.

Ciscar et al. (2018) assess the impacts of climate change on Europe by employing a variety of sector-specific models. They categorized the physical effects of climate change into eleven distinct sectors, including energy demand. Furthermore, Ciscar et al.(2018) employ Computable General Equilibrium (CGE) models, specifically the CAGE model, a static CGE model, to examine how these physical impacts of climate change disseminate throughout the economy. The study detailed how climate change influences productivity (for example, in agriculture) and capital on the supply side, as well as its effects on consumer behavior, such as spending to mitigate climate-related damages, on the demand side. For the impacts on energy, the study considered changes in heating and cooling demand, and those are reflected in the model as changes in obliged consumption.

There is a growing body of research on low energy demand, including NGFS Phase 4. Many of the studies we reviewed focus on the potential of different sectors to achieve a low energy demand future. However, a comprehensive analysis of the economic impact of following a low energy demand pathway is still lacking. Furthermore, as global warming intensifies, energy consumption will also be impacted, but this aspect of the Low Energy Demand literature has been largely untouched. Some climate change impact studies do address greenhouse gas emissions, temperature increases, and changes in energy demand. However, this aspect is not well considered in the low energy demand scenario analysis.

Therefore, the study develops and applies a climate module and a damage function for estimating the cooling and heating energy demand changes into the global CGE model. This allows to analyze the interlinkage between greenhouse gas emissions, global temperature rise, and cooling and heating energy consumption.

2.3. Methodology

This study applies the multi-regional computable general equilibrium (CGE) model, which is widely used for assessing the economic impacts of climate and energy-related policies as well as various scenarios. Based on this CGE model, the study develops and integrates the climate module and the damage function for calculating the cooling and heating energy demand in the global CGE model.

2.3.1. Data and Assumptions

This study applies the GTAP 11 Power Database, which is the most up-to-date database, and aggregates 160 region/country into 17 regions. The regional classification is based on the FUND(Climate Framework for Uncertainty, Negotiation and Distribution) model's 16 regional classification and additionaly separates the Republic of Korea as an individual country/region.

Table 1: Regional Classification

Label	Description
KOR	Republic of Korea
JPN	Japan
CHI	China, Hong Kong, Macau, North Korea, Mongolia
USA	United States of America
CAN	Canada
WEU	Western Europe
ANZ	Australia and New Zealand
CEE	Central and Eastern Europe
FSU	Former Soviet Union
MDE	Middle East
CAM	Central America
SAM	South America
SAS	South Asia
SEA	Southeast Asia
NAF	North Africa
SSA	Sub-Saharan Africa
SIS	Small Island States

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	Gas and Gas distribution	Gas, gdt
P_c	Petroleum and coal product	P_c
Agr	Agriculture	PDR, WHT, GRO, V_F, OSD, C_B, PFB, OCR, CTL, OAP, RMK, WOL, FRS, FSH
Ely	Electricity (non-renewable)	CoalBL, GasBL, OilBL, GasP, OilP, TnD
Ren	Electricity (renewable)	WindBL, HydroBL, HydroP, SolarP, OtherBL
Nuc	Electricity (nuclear)	NuclearBL
Mineral	Other Extractions	OXT
Food	Food	CMT, OMT, VOL, MIL, PCR, SGR, OFD, B_T
Cloth	Cloth	TEX, WAP, LEA
Paper	Paper	LUM, PPP
Chemical	Chemical	CHM, BPH, RPP, NMM
Metal	Metal	I_S, NFM, FMP
ICT	ICT and Computer	ELE, EEQ
Vehicle	Vehicle	MVH, OTN
Machine	Machinery and other	OME, OMF
Construc	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.

As the study utilized the recent GTAP 11 Power Database, the study set the year 2017 as the baseline year, and the year 2017 is the latest reference year of GTAP 11 (Aruiar et al. 2022). The study analyzed the mitigation pathways with and without LED measures. This CGE model can analyze the impacts not only on economic variables, such as GDP and GDI but also on employment. The model distinguishes skilled and unskilled employment based on the GTAP 11 database. GTAP 11 database classifies five types of occupations from the International Labour Organisation into two groups, which are skilled and unskilled employment[1].

[1] Unskilled Labor includes clearks, service/shop, and agriculture and other workers. Skilled labor includes tech/associate professionals and officials/managers/professionals.

2.3.2. Model Description[2]

A CGE (Computable General Equilibrium) model comprises a series of equations that methodologically assess how different segments of an economy interact with one another. By solving these equations, it identifies the equilibrium across the entire economy (Burfisher, 2016). Such a model operates on a dynamic recursive basis, establishing the conditions for equilibrium in each period. It accounts for equilibrium across various regions and commodities through (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). The model can conduct policy experiments impacting numerous countries and sectors at the same time.

The analysis using the CGE model offers a comprehensive overview of the impacts of transitions towards Net Zero, examining the potential advantages and challenges. It also explores how these countries' decisions regarding energy can influence greenhouse gas emissions and efforts to combat climate change. A range of policy suggestions will be made to guide the countries in fostering economic growth through net zero strategies while managing greenhouse gas emissions and minimizing the costs associated with these transitions.

The study utilizes a global multi-regional dynamic recursive CGE model, incorporating the production function based on a nested constant elasticity of substitution (CES) technology. The design of the nesting structure within the CGE model is based on the OECD ENV-LInakges model (Château et al. 2014).[3]

[Figure 4] illustrates the production technology's nesting structure, where each node within the nested framework represents a CES function expressed in calibrated share

[2] This section is prepared based on the previous EDITS report

[3] 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.

forms.

$$\boldsymbol{Q} = \overline{\boldsymbol{Q}}\left[\sum_i \boldsymbol{\theta}_i \left(\frac{\boldsymbol{X}_i}{\overline{\boldsymbol{X}}_i}\right)^{\boldsymbol{\rho}}\right]^{\boldsymbol{1/\rho}}, \boldsymbol{\rho} = \frac{\boldsymbol{\sigma-1}}{\boldsymbol{\sigma}},$$

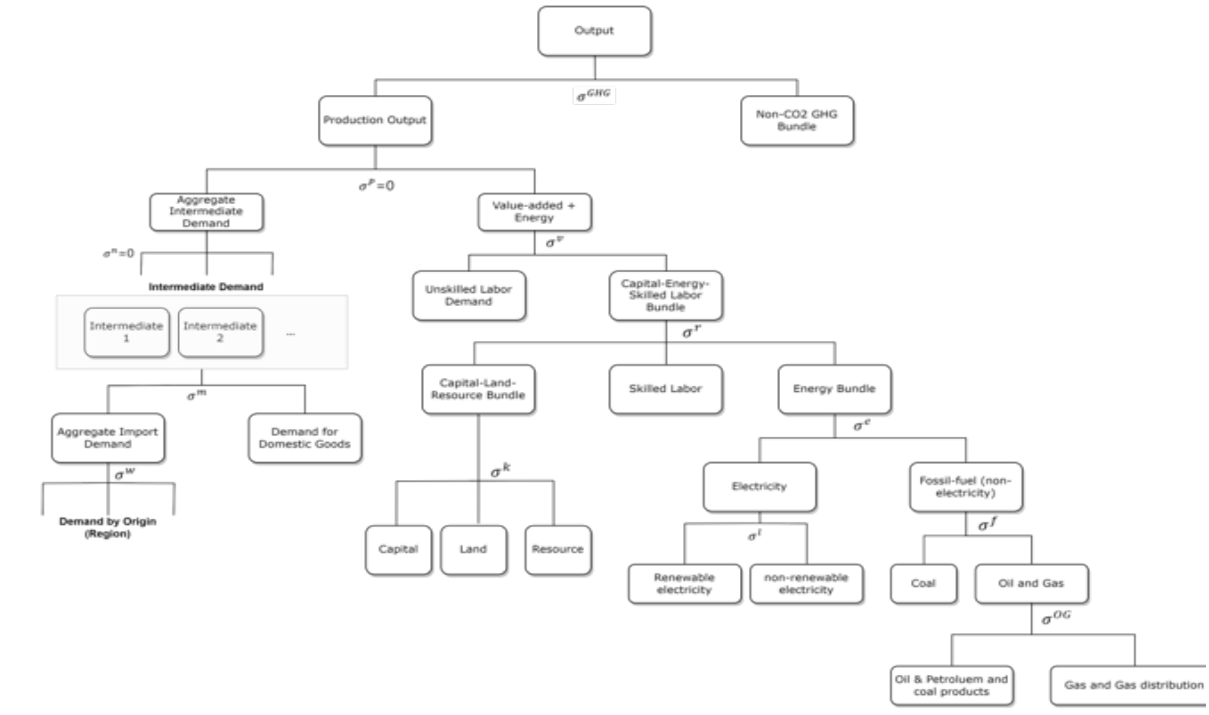
where Q is the amount of output and the Xi is the i-th input. $\boldsymbol{\sigma}$ is the constant elasticity of substitution between inputs and the upper bars indicate the base year values. $\boldsymbol{\theta_i}$ is the value share of i-th input. The equilibrium conditions to the CES technologies are as follows:

$$\boldsymbol{X_i} = \boldsymbol{\lambda_i^{\sigma-1}\theta_i}\left(\frac{\overline{\boldsymbol{\beta}}}{\overline{\boldsymbol{P}}_i}\right)^{\boldsymbol{1-\sigma}}\left(\frac{\boldsymbol{\beta}}{\boldsymbol{P_i}}\right)^{\boldsymbol{\sigma}} Q, \boldsymbol{\beta} = \overline{\boldsymbol{\beta}}\left[\sum_i \boldsymbol{\theta}_i \left(\frac{\boldsymbol{P_i}}{\overline{\boldsymbol{P}}_i}\right)^{\boldsymbol{1-\sigma}}\right]^{\boldsymbol{1/(1-\sigma)}},$$

where P_i is the price of i-th input and β is the output price.

The equilibrium conditions outlined previously are applicable across all CES technologies, encompassing every sub-node within the nested CES functions. These conditions extend to various economic relationships, including the substitution between domestic and imported goods, the transformation between domestic versus export demands, and competitions among regions for international transport services.

Figure 4. Nesting Structure



Source: Author's own elaboration.

Dynamic recursive CGE models determine equilibrium on a period-by-period basis. In this approach, households are modeled to make immediate decisions, while the model's inherent dynamics allow for the accumulation of physical capital over time. This accumulated capital then becomes integrated into the production processes of future periods, reflecting the ongoing evolution of the economy's productive capacity.

The Armington specification is employed within the international trade block of the model through a two-level nested CES structure. At the uppermost level of this structure, domestic agents decide on the optimal mix between goods produced domestically and those aggregated from imports. Following this, at the next level down, the agents distribute their demand for these aggregated imports among various trading partners (Jung et al. 2021).

For the household sector, the model assumes a Cobb-Douglas utility function. The government, on the other hand, levies various types of taxes including income taxes, taxes on factors of production, consumption taxes, and tariffs. Its spending decisions are modeled to follow a Cobb-Douglas production function as well, with the total amount of government consumption fixed as a constant proportion of real GDP. To maintain the balance, the government's budget surplus or deficit is held constant at the level observed in the base year, requiring endogenous adjustments to income tax rates as necessary. Similarly, the current account surplus or deficit for each region is assumed to remain constant at its base year value, ensuring external balance within the model's framework.

Table 2: 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	$\sum_{(r',i)} Pfob_{r,r',i} Qtrade_{r,r',i} + \sum_i Ptrnserv_{r,i} Qtrnserv_{r,i} + ForegnSaving_r = \sum_{(r',i)} Pcif_{r',r,i} Qtrade_{r',r,i}$
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'*
$Ptrnserv_{r,i}$: Price of international transport service *i* provided by region *r*
$Qtrnserv_{r,i}$: 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*
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.

Table 3: Key Parameters

Parameter	Notation	Value
Substitution between labor and KTRE bundle	σ^{v}	0.2 for coal, oil and gas, 1.26 for p_c and gdt, 0.24 for agr, 1.26 for ely, ren and hom, 1.2 for mfr, 1.4 for cnt, 1.37 for ser, 1.68 for trn; GTAP data (esubva) is used
Armington elasticity: domestic versus import	σ^{m}	GTAP data (esubdm) is used: 3.8–16.0, depending on sectors
Armington elasticity: import sources	σ^{w}	GTAP data (esubm) is used: 3.8–34.4, depending on sectors
Substitution between KTR bundle, energy, and skilled labor	σ^{r}	0.029 ~ 0.654 depending on sectors
Substitution between capital, land, and natural resources	σ^{k}	0.2
Substitution between electricity and fossil fuel	σ^{e}	2 0 for fossil-fuel
Substitution between renewable and nonrenewable electricity	σ^{l}	2
Substitution between fossil energies (Coal and Oil and Gas)	σ^{f}	0.55 for new, 0.06 for old 0 for fossil-fuel
Substitution between Oil and Gas	σ^{OG}	1 for new, 0.125 for old 0 for fossil-fuel

GTAP = Global Trade Analysis Project, KTR = Capital-Land-Natural Resource, KTRE = Capital-Land-Natural Resource-Energy.

Source(s): Author's own elaboration.

The authors utilized the GTAP 11 Power database to establish a Global Social Accounting Matrix, which is a key input data for CGE analysis (Aguiar et al. 2022), and the model used the updated SSP2 scenario from EU Navigate project for model calibration. This update includes the impacts of COVID-19 on the economic growth. The model is calibrated by adjusting total factor productivity to reproduce the updated 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 the GTAP 11 power database. Although the GTAP 11 power 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 the GTAP 11 database is somewhat outdated as its reference year is 2017, which would not properly reflect the global economy today.

2.3.3. Climate Module

To analyze the impacts of climate-induced energy demand change, we developed the climate module, which can incorporate the greenhouse gas emissions from CGE model and calculate the level of global temperature increase. The climate module from FUND (Climate Framework for Uncertainty, Negotiation and Distribution) was applied to the global CGE model.

To individually consider Korea as an independent region, the study separated Korea from JPK (Japan and Korea) in FUND model and applied the same parameter to Korea. The calculation process of the climate module was (1) to calculate the carbon dioxide concentration in the atmosphere, (2) to calculate the radiative forcing, and (3) to calculate the global and regional temperature rise.

First, the carbon dioxide calculation in the atmosphere was calculated based on the following equation:

$$C_t = C_{t-1} + E_{t-1} - \beta\left(C_{t-1} - C_{pre-industrial}\right)$$

$$C_t: Carbon\ Dioxide\ concentration\ at\ time\ t$$

$$C_{pre-industrial}: Carbon\ Dioxide\ concentration\ (pre-industrial)$$

$$E_t: CO2\ Emission$$

$$t: time$$

The original FUND model's time step was from 1950 to 2300, so the climate module started from 1950. The initial concentration from the FUND model was 310.75 ppm,

but the current concentration reached much higher than the FUND's initial value. Thus, the study updated it to NOAA's CO2 concentration value of 405.22 ppm in 2017 as the initial value for CO2 concentration.

Next, the FUND model applied a five-box model for calculating the concentration, and each box has a different decay rate of carbon dioxide. The total CO2 concentration was the sum of the all five boxes.

$$BOX_{i,t} = \alpha_i BOX_{i,t-1} + 0.000471\gamma_i E_t$$

$$BOX_{i,t}: i-th\ BOX\ at\ time\ t$$

$$a_i: decay\ rate\ of\ i-th\ BOX$$

$$\gamma_i: share\ of\ emission$$

While carbon dioxide concentration was calculated based on the Box system, the other greenhouse gases, such as CH4, N2O, and SF6, were considered when calculating the radiative forcing. The following equation was used to calculate the radiative forcing, which becomes the basis for calculating the global temperature increase.

$$\begin{aligned} RF_t = {} & 5.35 \ln\left(\frac{CO2_t}{275}\right) + 0.036 * 1.4\left(\sqrt{CH4_t} - \sqrt{790}\right) + 0.12\left(\sqrt{N2O_t} - \sqrt{285}\right) \\ & - 0.47 \ln\left(1 + 2.01 * 10^{-5} CH4_t^{0.75} 285^{0.75} + 5.31 * 10^{-15} CH4_t^{2.52} 285^{1.52}\right) \\ & - 0.47 \ln\left(1 + 2.01 * 10^{-5} N2O_t^{0.75} 790^{0.75} + 5.31 * 10^{-15} N2O_t^{1.52} 790^{2.52}\right) \\ & + 2 * 0.47 \ln\left(1 + 2.01 * 10^{-5} 790^{0.75} 285^{0.75} + 5.31 * 10^{-15} 790^{2.52} 285^{1.52}\right) \\ & + 0.00052(SF6_t - 0.04) + rfSO2_t \end{aligned}$$

$$RF_t: Radiative\ forcing\ at\ time\ t$$

After the radiative forcing was calculated, the global mean temperature change was calculated by the following equation, and the regional mean temperature change was calculated by multiplying the regional parameter by the global mean temperature change.

$$Temp_t = \left(1 - \frac{1}{\rho}\right) Temp_{t-1} + \frac{1}{\rho} * \frac{CS}{5.35\ ln2} RF_t$$

$$\rho = \max(a + v^1 CS + v^q CS^2, 1)$$

$$REG_Temp_t = REG * Temp_t$$

$$Temp_t: Global\ mean\ temperature\ increase\ (above\ pre-industrial\ level)$$

$$CS: Climate\ Sensitivity\ (default: 3)$$

$$\rho: e-folding\ time$$

$$\upsilon^1 = 29.1;\ \upsilon^q = 0.001$$

$$REG: Regional\ Temperature\ Parameter$$

The greenhouse gas emission information, including CO2, N2O, CH4, SF6, etc., was generated from the global CGE model and went to the climate module for calculating the global mean temperature increase.

2.3.4. Climate-induced Energy Demand Changes

The model adopted the FUND model's damage function, which estimated the additional energy consumption for cooling and heating due to climate change. This considers the changes in space cooling and heating energy demand. 'EXP' indicates the additional expenditure for space cooling and heating.

$$EXP_{t,r}^{Heat} = a_r^{Heat} Y_{1990,r} \left(\frac{\text{atan}\left(Temp_{t,r} - Temp_{1990,r}\right)}{\text{atan}\ 1}\right)\left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\epsilon_h}\left(\frac{pop_{t,r}}{pop_{1990,r}}\right) / CumAEEI_{t,r}^{1990}$$

$$EXP_{t,r}^{Cool} = a_r^{Cool} Y_{1990,r}\left(Temp_{t,r} - Temp_{1990,r}\right)^{\zeta}\left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\epsilon_c}\left(\frac{pop_{t,r}}{pop_{1990,r}}\right) / CumAEEI_{t,r}^{1990}$$

$$a_r^{Heat}, a_r^{Cool}: parameter\ of\ climate\ impacts\ on\ heating\ and\ cooling$$

$$cumAEEI_{t,r}^{1990}: Cumulative\ Autonomous\ Energy\ Efficiency\ Improvement\ since\ 1990$$

$$\epsilon_c, \epsilon_h: parameter\ (the\ impact\ of\ economic\ growth\ for\ heating\ and\ cooling)$$

$$\zeta: parameter\ (the\ impact\ of\ global\ temperature\ change\ on\ cooling\ expenditure)$$

For calculating the cumulative Autonomous Energy Efficiency Improvement (AEEI), the study included the FUND model's initial AEEI and cumAEEI until 2017, and then, the rate of energy efficiency improvement of the global CGE model is applied to calculate the cumAEEI.

After the calculation of the additional expenditure on cooling and heating, we

integrated this impact to the model by shifting the share parameter of ‘KTRE’ bundle, which is the energy-capital-skilled labor bundle. We assumed that the share of ‘energy’ bundle in ‘KTRE’ bundle shifts. The change of the ‘KTRE’ bundle’s share parameter is offset by shifting the share parameter of skilled labor in the ‘KTRE’ bundle in order to maintain the sum of all share parameters, which should be remain at 1.

2.4. Scenarios

For analyzing the climate-induced impacts on energy demand changes and the Low Energy Demand scenarios, we constructed four different scenarios. The first scenario is the Business-as-Usual (‘BAU’) scenario, and this scenario follows the updated SSP2 GDP and population projections. Also, a low level of carbon price is introduced before 2020, and it reaches 2020 carbon prices in 2020 and continues to remain at the same level onwards. The detailed carbon prices will be explained in the following section. Next scenario is Energy Expenditure (‘E_EXP’), and this scenario additionally considers the climate-induced energy demand changes as described in the previous section. Thus, this scenario calculates the impacts of climate change on the space cooling and heating energy demand and integrates them into the model. Thus, this scenario can analyze how the global mean temperature change can affect the changes in global and regional cooling and heating energy demand and also how those changes in cooling and heating energy demand affect the global economy and greenhouse gas emissions.

The third scenario is NZ Carbon Pricing scenario (‘CPrice’). This scenario is built on the E_EXP scenario and additionally considers the carbon prices from IEA Net Zero. There is no advanced low-carbon technologies, such as direct air capture, carbon capture and storage, and hydrogen.

Table 4. Regional Carbon Prices in 2020, 2030, 2040, 2050

	CPZ30	CPZ40	CPZ50
ANZ	140	205	250
SIS	25	85	180
CHI	89.728	159.687	199.916
JPK	140	205	250
KOR	140	205	250

SEA	44.575	107.586	186.023
SAS	82.196	150.995	197.599
CAN	140	205	250
USA	140	205	250
CAM	25	85	180
SAM	71.012	136.057	199.702
WEU	140	205	250
CEE	126.668	191.088	241.885
FSU	26.696	86.77	181.033
MDE	47.841	108.834	193.903
NAF	25	85	180
SSA	65.172	131.352	192.36
Source: Author's calculation based on the carbon prices of IEA Net Zero 2050 scenario			

The last scenario is LED scenario ('LED'). In addition to CPrice scenario, this scenario includes two additional assumptions describing the demand changes towards low energy consumption. In the previous studies, the major low demand measure discussed was energy efficiency improvement. Thus, the model assumes the energy efficiency improvement in industrial sectors as well as the efficiency improvement in household's energy and electricity consumption. The study assumes the energy efficiency improvement by 1% per year for Global North and 1.5% per year for Global South. Next, the study assumed that the household's energy consumption behavior changes towards lower energy consumption. In the model, the study adjusted the share parameter of energy and electricity consumption to be decreased by 1.5% (Global South) and 1.75% (Global North). We established this scenario based on the assumptions that the energy efficiency improvement can happen faster in Global South, but the changes in energy consuming behaviors, including lifestyle change, can happen faster in Global North.

These four scenarios are considered to analyze the climate-induced energy demand changes, estimate the impacts of Carbon Pricing on economy, and find the evidence of how Low Energy Demand measures can reduce the economic burden of the low-carbon transition.

Table 5. Description of Scenarios

Scenario	Key assumptions
BAU	Baseline scenario

	GDP and population forecast in updated SSP2 scenarios
EXP	BAU Scenario with climate-induced energy demand changes
CPrice	EXP Scenario + NGFS Phase 3 Carbon Pricing (from REMIND model)
LED	CPrice Scenario's emission pathway + Energy efficiency improvement in industries and household's energy consumption by 1% (Global North) and 1.5% (Global South) Share parameter adjustment by 1.5% and 1.75% per year in Global South and Global North, respectively

2.5. Scenario Anaylsis

[Figure 5] shows the changes in the global greenhouse gas emissions by scenario. The result indicates that EXP scenario shows a higher greenhouse gas emissions compared to the BAU scenario. In other words, the climate-induced energy demand changes can positively affect the greenhouse gas emissions. Also, the introduction of the carbon pricing can significantly reduce the global greenhouse gas emissions. This model does not consider the low carbon technologies, such as CCS and hydrogen, so it does not reach the Net Zero emissions and show some remaining emissions. Note that the IEA's Net Zero carbon pricing is not high enough to lead the substantial reductions in greenhouse gas emissions in this model, and the greenhouse gas emissions remain a slight lower than today's greenhouse gas emissions.

The climate module estimates the global mean temperature increase by scenario, and the result indicates that the greenhouse gas emissions can go beyond 2-degree in BAU and EXP scenarios, and the introduction of carbon pricing can lower the global mean temperature increase, but the global mean temperature increase becomes slightly over 2-degree in 2050. LED scenario follows the CPrice scenario's emission pathways, so the global mean temperature increase of LED scenario is same as that of CPrice scenario.

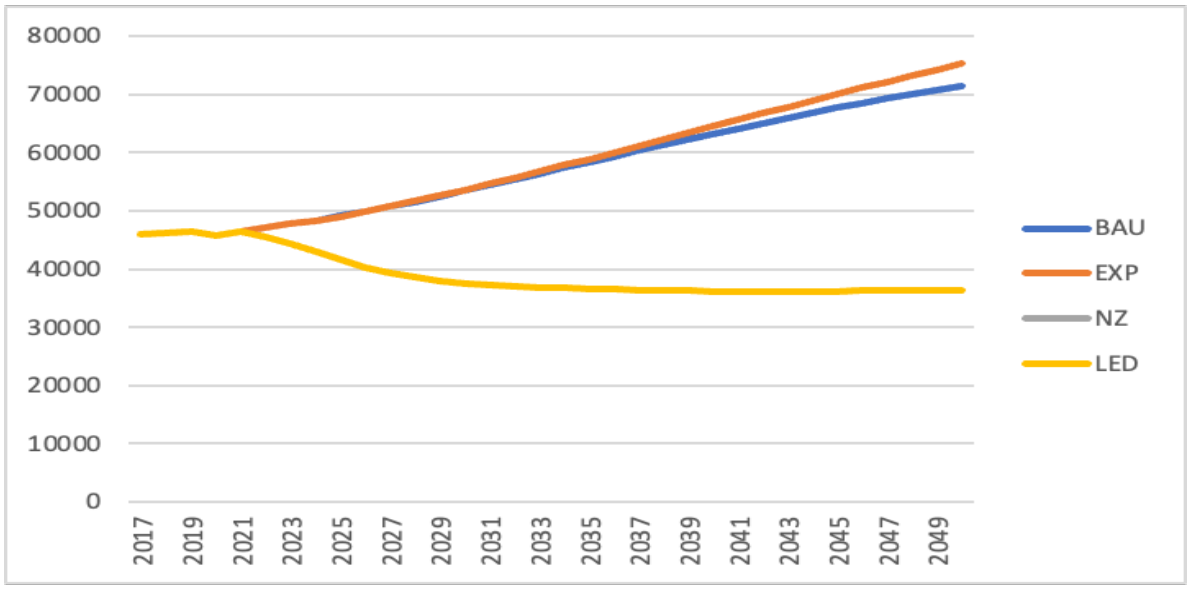


Figure 5. Global Greenhouse Gas Emissions (Unit: MtCO2eq)

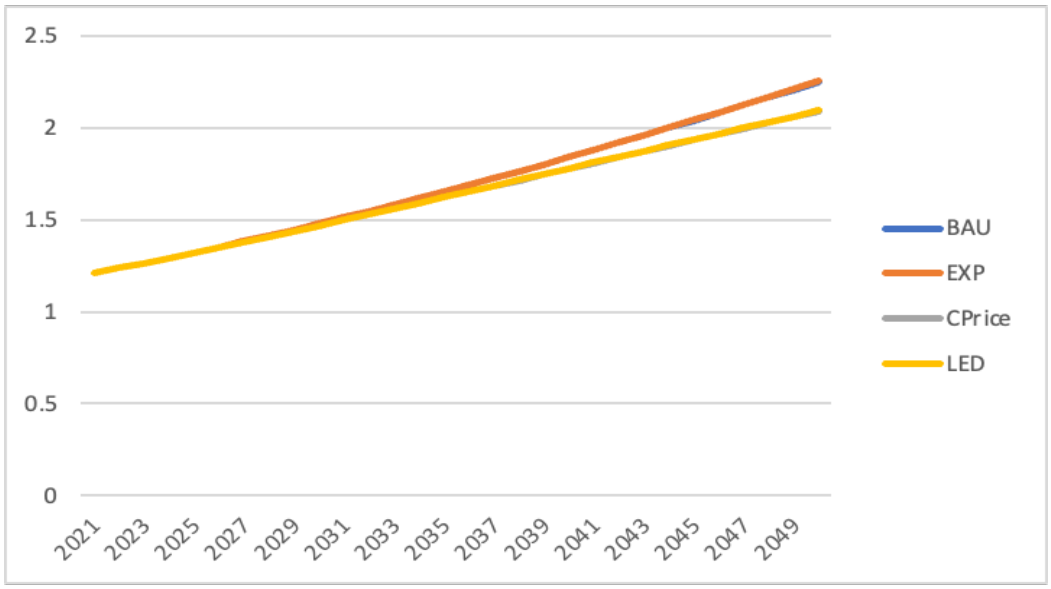


Figure 6. Global temperature change (2021-2050)

The following [Figure 7] also indicates that climate change would increase the final energy demand relative to the BAU level. The result shows that there can be 3.68% of the final energy demand increase in 2021-2050 relative to the BAU level. The Net Zero carbon prices lead to a significant reduction in the global Final Energy Demand, and the Low Energy Demand measures, such as energy efficiency improvement and household energy consumption reductions, can further reduce the final energy demand.

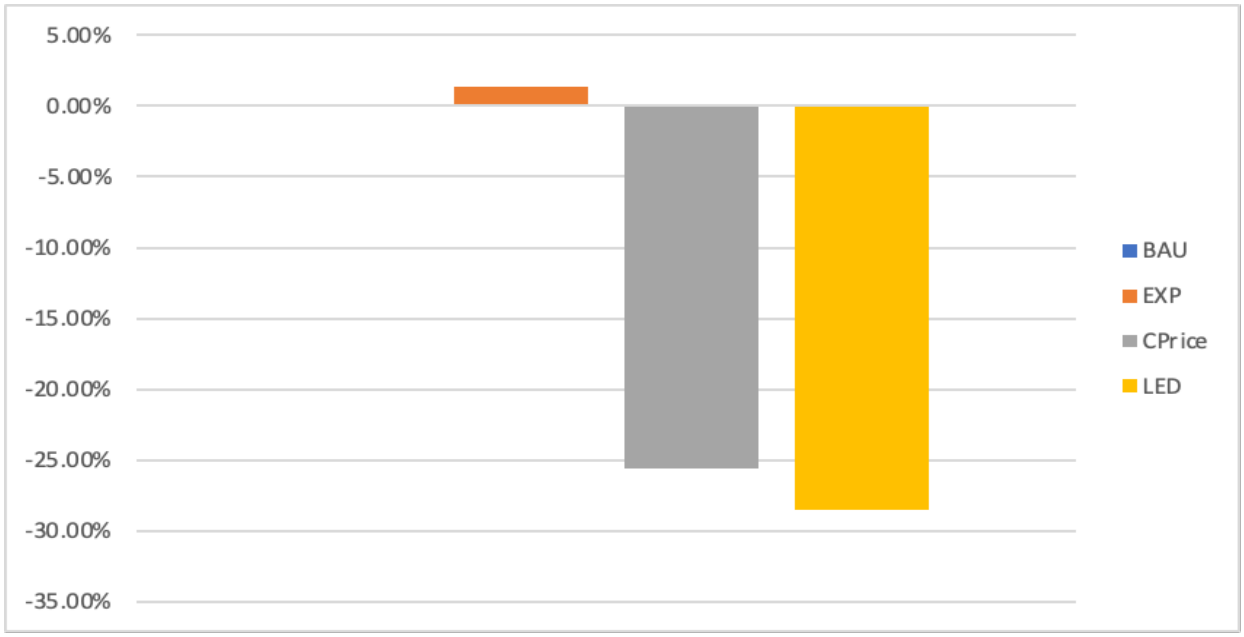


Figure 7. Changes in global Final Energy Demand (2021-2050) (Unit: % difference from BAU)

The changes in real GDP indicate that the LED scenario can reduce economic losses from carbon pricing. The Net Zero scenario leads to about 3.6% losses in real GDP (2021-2050) relative to the BAU, and the LED scenario reduces the losses in real GDP to -0.16% relative to the BAU, which is the smallest losses in real GDP compared to the other EXP and CPrice scenarios.

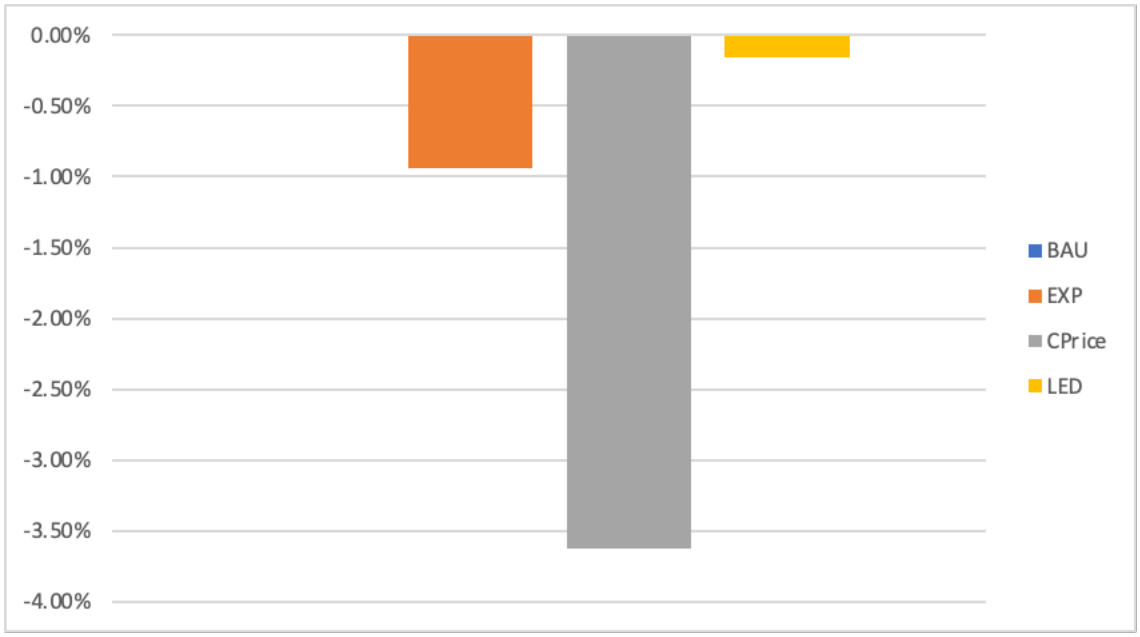


Figure 8. Changes in real GDP (% difference from BAU)

The global production and investment show that the fossil-fuel-related sectors, such as coal, gas, oil, and petroleum and coal products, and the non-renewable electricity sector experience significant losses in production and investment. Particularly, coal, oil, and petroleum and coal product sectors experience substantial losses. On the other hand, the renewable and nuclear electricity sectors can experience significant increases in global production and investment.

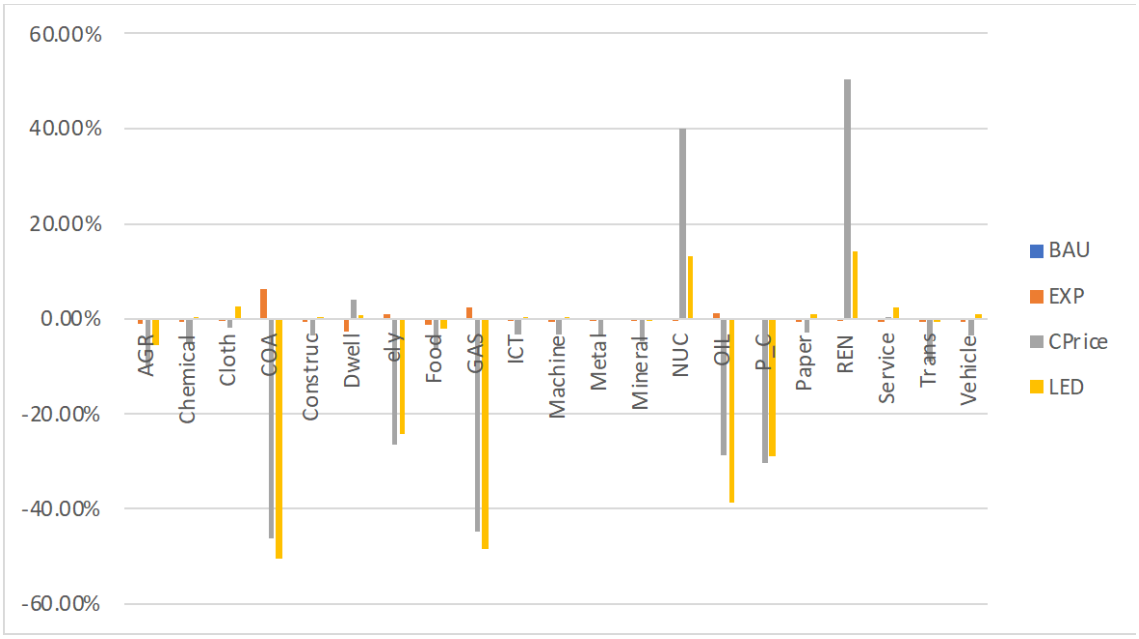


Figure 9. Changes in Global Production by Sector (2021-2050) (% difference from BAU)

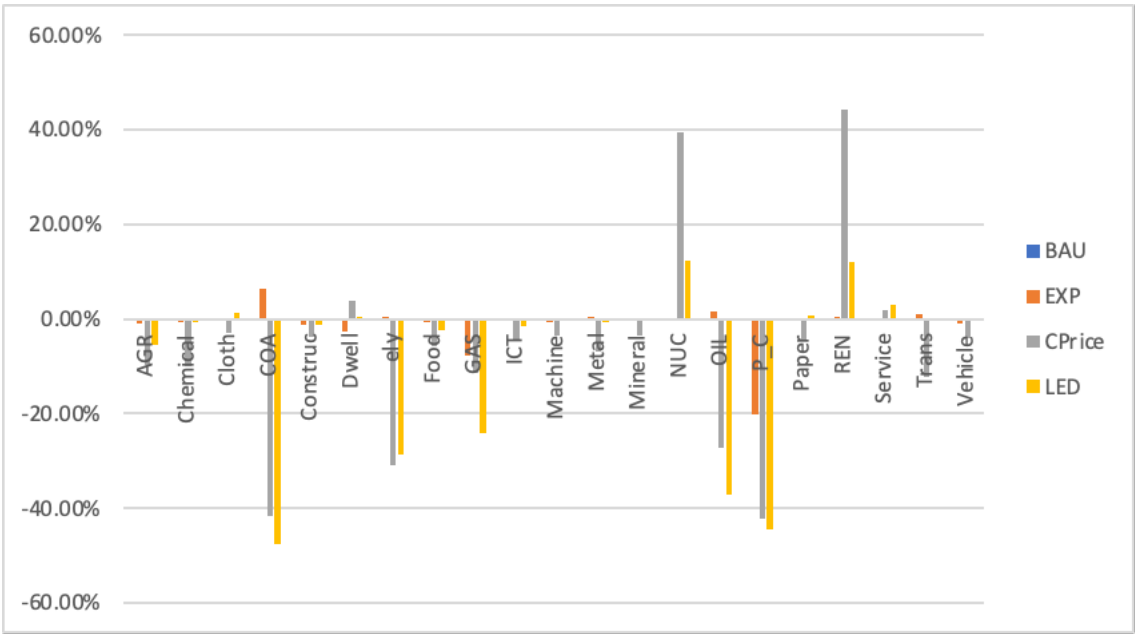


Figure 10. Changes in Global Investment by Sector (2021-2050) (% difference

from BAU)

In the case of Korea, there can be some negative climate-induced impacts on greenhouse gas emissions. Although the changes in the greenhouse gas emissions (2021-2050) indicate -0.77% relative to the BAU level, the impacts are not significant. The carbon prices can reduce greenhouse gas emissions by about 30% relative to the BAU level. LED Scenario follows the greenhouse gas emission pathway of the CPrice scenario, so there is no difference between the two scenarios.

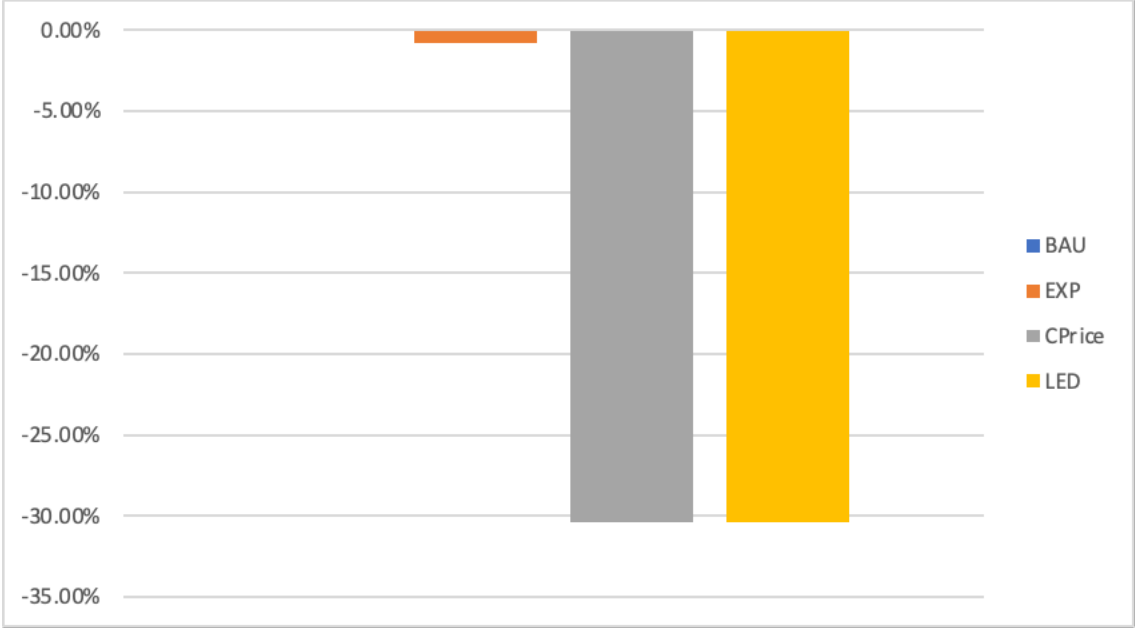


Figure 11. Changes in GHG emissions in Korea (2021-2050) (% difference from BAU)

For the final energy demand, the climate-induced impacts on energy demand in Korea (2021-2050) can be a slight decrease of 0.63% relative to the BAU while the global temperature increase can lead to some increase in global final energy demand. Similar to the global case, the carbon prices lead to some decrease in the final energy demand, and the final energy demand becomes about 10% below the BAU scenario. The energy efficiency improvement and the reductions in household energy consumption can further reduce the final energy demand relative to the BAU level. LED Scenario can lead to about 12% reductions in the final energy demand relative to the BAU level.

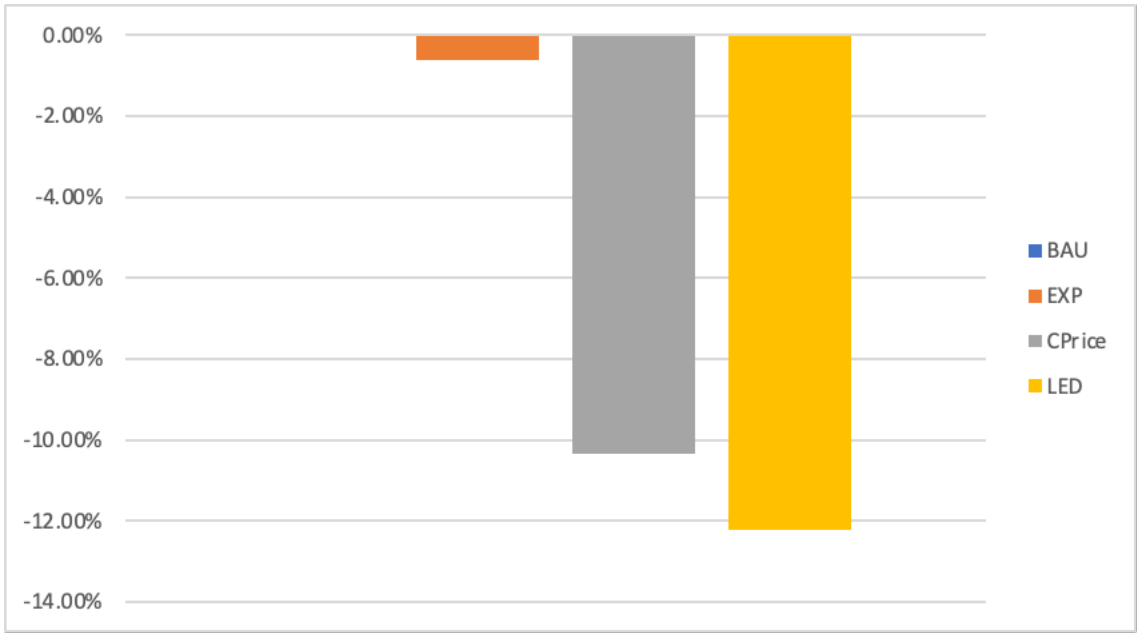


Figure 12. Changes in Final Energy Demand in Korea (2021-2050) (% difference from BAU)

The introduction of carbon pricing could bring slight economic losses (2021-2050) relative to the BAU in Korea. However, the introduction of demand measures, such as energy efficiency improvement and household energy consumption reduction, can bring economic gains and lead to the highest economic growth among the four scenarios.

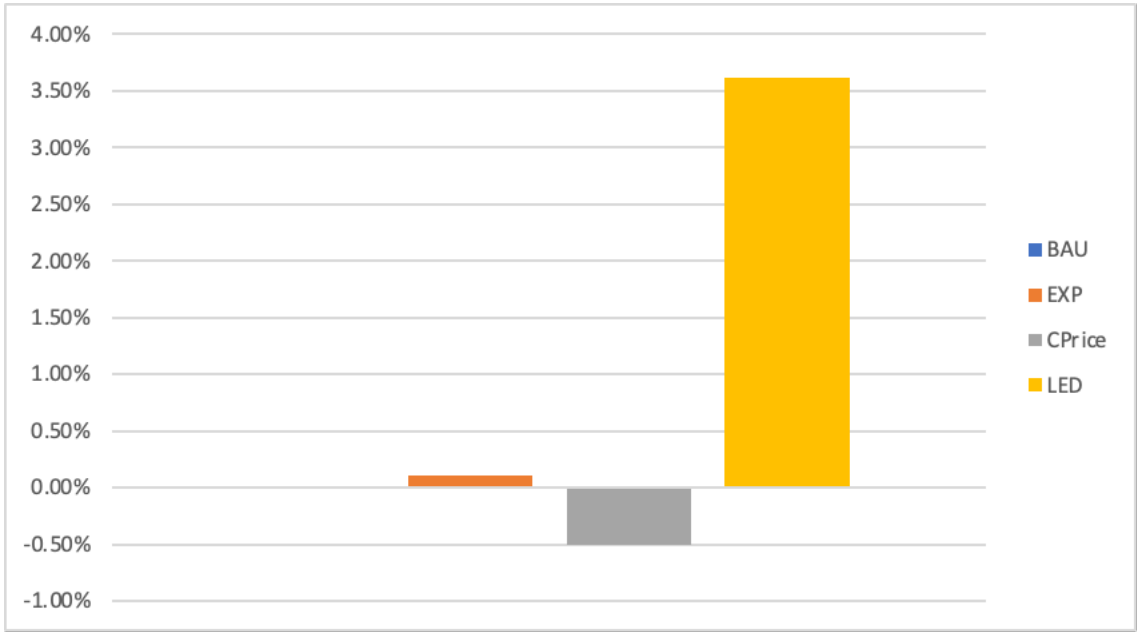


Figure 13. Changes in real GDP in Korea (% difference from BAU)

The following [figure 14] shows the changes in sectoral production over 2021-2050 in Korea. The sectoral production (2021-2050) relative to the BAU shows a similar result to the global production. The fossil-fuel-related sectors, such as oil and petroleum and coal products, could experience a significant reduction in production. An interesting result is that Korea could experience a relatively higher increase in nuclear electricity compared to renewable electricity.

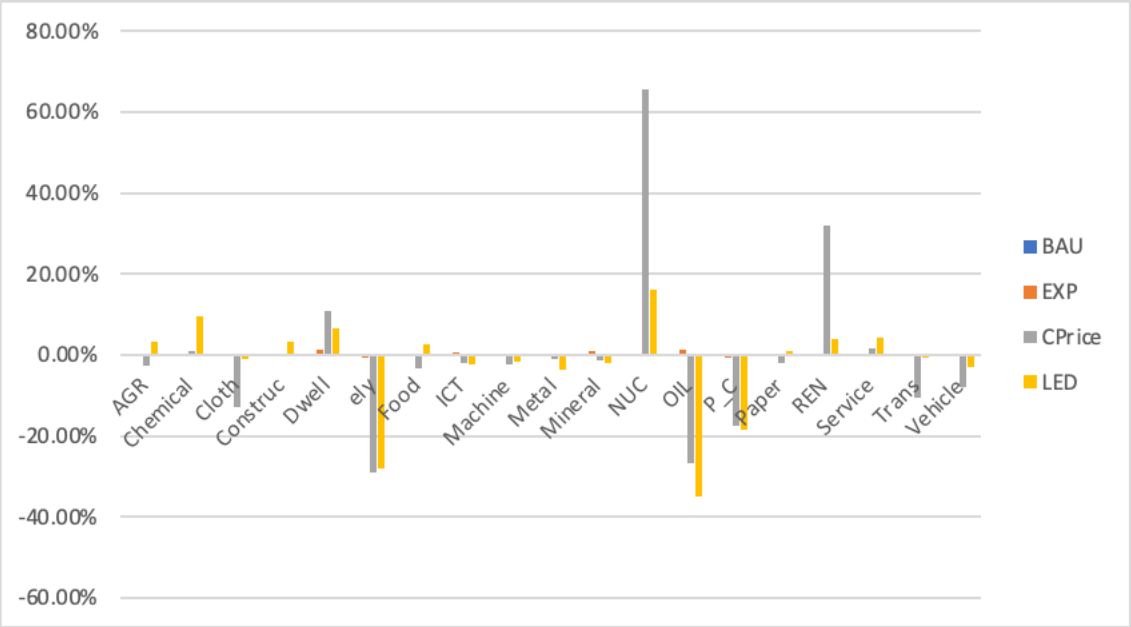


Figure 14. Changes in sectoral production (2021-2050) in Korea (% difference from BAU)

The changes in investment (2021-2050) indicate a similar picture as the changes in production. The changes in production and investment suggest that the introduction of carbon pricing can lead to a significant sectoral transition. The low energy demand measures can alleviate the losses or bring economic gains in many non-energy-related sectors, such as agriculture, chemical, cloth, service, transport, and so on, compared to the CPrice scenario. In other words, the result implies that the low-demand measures can reduce the economic costs of transitions.

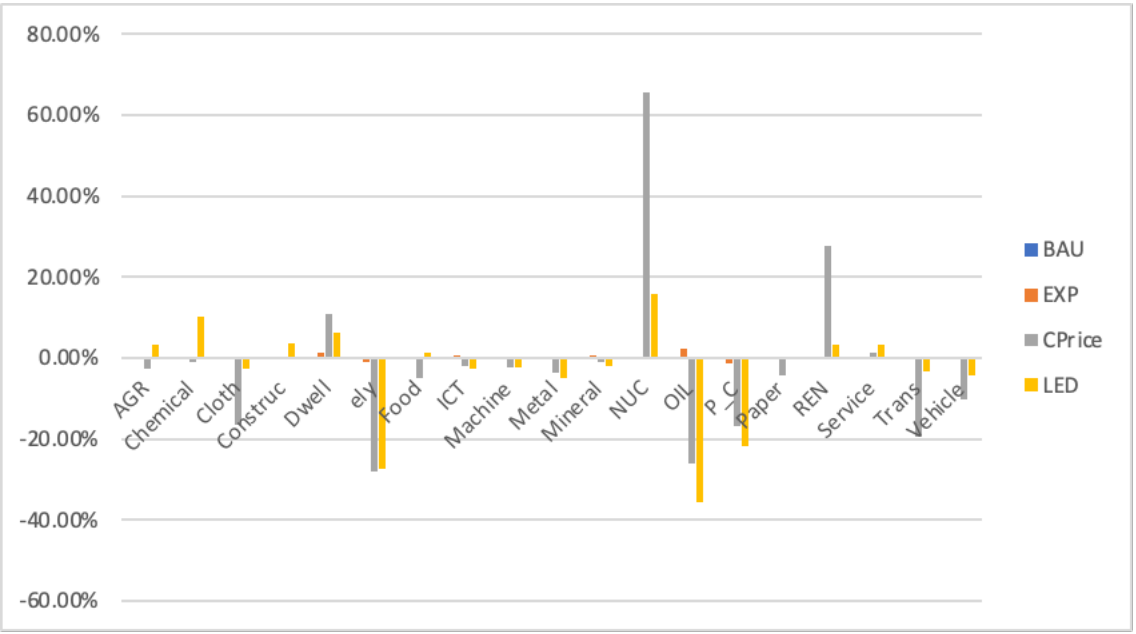


Figure 15. Changes in sectoral investment (2021-2050) in Korea (% difference from BAU)

For employment, carbon pricing could bring some positive changes in Korea's employment (2021-2050), and the low energy demand measures can bring the largest increase in employment in Korea. The LED scenario shows about a 4% increase in employment (2021-2050) relative to the BAU level.

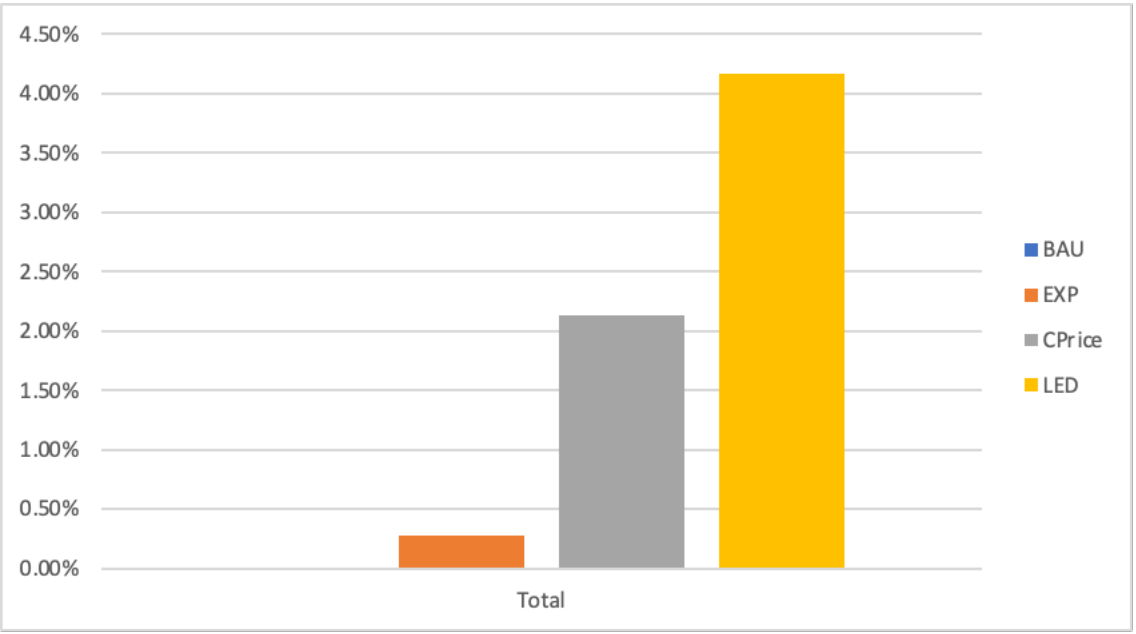
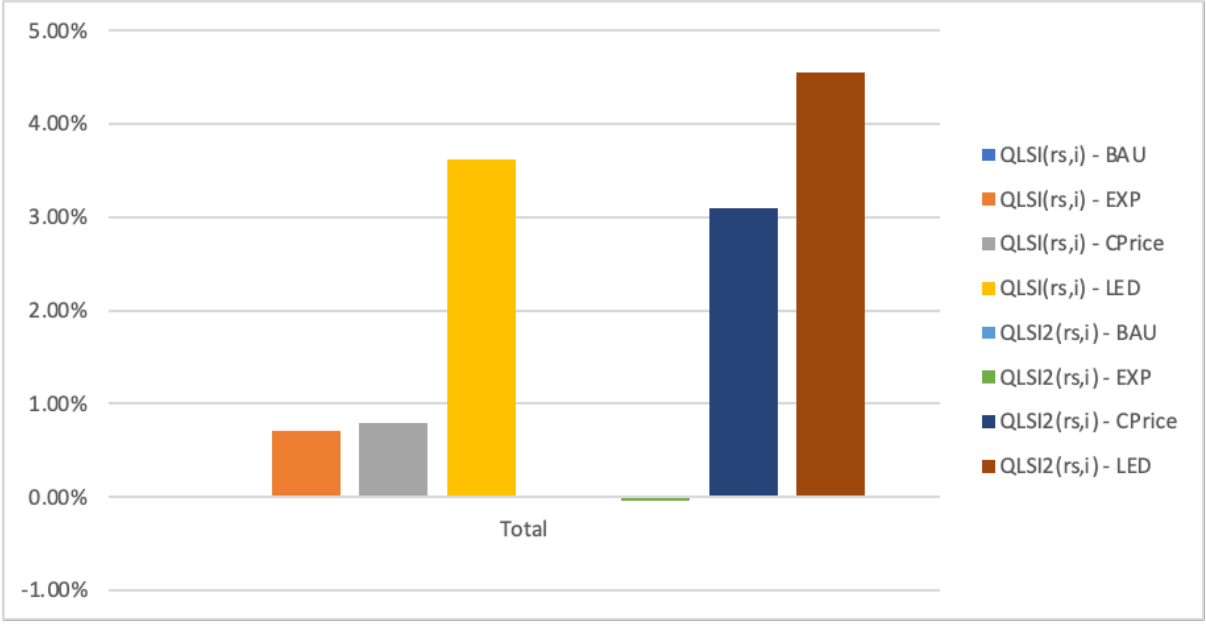


Figure 16. Changes in employment (2021-2050) in Korea (% difference from BAU)

For skilled and unskilled employment, both show a substantial increase when the low energy demand measures are employed. Particularly, unskilled employment increases significantly when carbon pricing is introduced compared to the BAU level. Skilled employment does increase but does not change much in EXP and CPrice scenarios. Skilled employment can improve substantially in the LED Scenario. LED Scenario can bring significant increases in skilled and unskilled employment.



Note: QLSI (Skilled Labor) and QLSI2 (Unskilled Labor)

Figure 17. Changes in Skilled and Unskilled Employment (2021-2050) (% difference from BAU)

2.6. Conclusion

This study utilizes the global CGE model and applies the climate module and the damage function, estimating the changes in cooling and heating energy demands due to temperature increase from the FUND model, an integrated assessment model. This application allows us to analyze the global temperature change based on the greenhouse gas emissions from the CGE model and to find how global warming can increase energy demands and corresponding greenhouse gas emissions and exacerbate the mitigation efforts. The result suggests that the global energy demand can increase due to the global temperature increase, and the greenhouse gas emissions can increase accordingly. Particularly, the increasing pace of greenhouse

gas emissions becomes faster as the global temperature rises, so climate-induced energy demand changes can bring some challenges in achieving low energy demand. The result indicates that global temperature increase can reach and go beyond 2-degree in the 2040s.

The introduction of carbon pricing can reduce greenhouse gas emissions and limit some global temperature increases. In this study, carbon prices in IEA's Net Zero scenario are used, but the results imply that higher carbon prices are necessary to reduce the greenhouse gas emissions further to bring the greenhouse gas emissions to near zero since there is no carbon capture or other innovative low-carbon technologies, which can contribute to achieving Net Zero.

An important implication is that the implementation of low energy demand measures, such as energy efficiency improvement and household's energy consumption reduction can bring substantial benefits in Korea. While reducing the same level of greenhouse gas emissions as CPrice scenario, LED scenario can further reduce the final energy demand (2021-2050) in Korea. Also, it can bring substantial economic benefits, and the LED scenario's real GDP (2021-2050) can exceed the real GDP of BAU scenario.

Moreover, the low energy demand measures can bring benefits in production and investment in non-energy sectors. The introduction of carbon pricing can reduce the production and investment, particularly in fossil-fuel-related sectors. For non-energy sectors, the impacts of carbon pricing are not significant as fossil-fuel-related sectors, but a number of non-energy sectors experience some negative impacts on production and investment. However, the LED scenario can bring positive gains in investment and production in non-energy sectors in general. In sum, the results suggest the potential of the measures for reducing energy demand on facilitating the mitigation efforts.

3. Structural Decomposition Analysis for the Impact of Low Demand Scenario

3.1. GHG emission forecast results based on scenarios

This study utilizes greenhouse gas emissions projections for major ASEAN countries through the Computable General Equilibrium (CGE) model developed by the Korea Environment Institute (2021). Using the scenarios set by Kim (2022), we compare and analyze the GHG emission factors of each scenario for Korea.

There are three scenarios used for Kaya's Identity analysis. The first is the baseline scenario ('BAU') for GHG emissions. This is a scenario in which countries around the world achieve economic growth assumed exogenously without introducing climate policies to reduce GHGs in the global CGE model. Additionally, the BAU scenario also reflects changes in cooling and heating energy demand due to rising global temperatures.

The second scenario is a scenario called Net Zero (NZ) to reduce GHG emissions to introduce a carbon price to achieve 2030 Nationally Determined Contributions (NDC) and carbon neutrality by 2050. This scenario adopts IEA's Net Zero 2050 scenario's carbon prices in 2030, 2040, and 2050.

The third scenario represents the low energy demand (LED) scenario. Factors considered in this scenario include improving industrial energy efficiency, improving household energy consumption-related efficiency, and reducing energy consumption. Industrial energy efficiency is assumed to improve by 1% each year in developed countries and 1.5% in developing countries. Efficiency improvements related to household energy consumption are also expected to increase equally. Reduction in household energy consumption will reduce energy-related consumption by 1.5% per year in the Global South and 1.75% per year in the Global North, and this assumption is applied to consume other commodities.

The following [Table 6] summarizes the key variables of three scenarios.

Table 6. Summary of Scenario Results

Scenario	Indicator	Unit	2020	2030	2040	2050
BAU	Papulation	Mill.	51.89	51.95	51.00	48.45
	GDP	Bill. USD	1,687.24	2,224.42	2,725.45	3,154.47
	Energy	M. TOE	187.19	209.67	237.02	262.11
	GHG	MtCO2eq	661.55	715.35	792.39	855.51
CPrice	Papulation	Mill.	51.89	51.95	51.00	48.45
	GDP	Bill. USD	1,687.24	2,223.26	2,706.66	3,098.57
	Energy	M TOE	187.19	183.12	209.32	241.23
	GHG	MtCO2eq	661.55	518.15	502.69	501.02
LED	Papulation	Mill.	51.89	51.95	51.00	48.45
	GDP	Bill. USD	1,687.24	2,266.19	2,837.60	3,360.69
	Energy	M TOE	187.19	183.06	203.84	226.23
	GHG	MtCO2eq	661.55	518.15	502.69	501.02

3.2. Kaya's Decomposition Analysis

The Kaya identity is a method of analyzing changes in carbon dioxide emissions over a certain period of time. (Kaya and Yokobori, 1997). The amount of change in carbon dioxide emissions in a specific country or region subject to analysis in a given period is determined by economic and social factors such as energy use, type of energy source, scale of national production, and population. Through Kaya's identity, the factors that change carbon dioxide emissions over a certain period of time can be analyzed. The Kaya identity can be expressed as follows, and LMDI (Logarithm mean Divisia index) method is applied (Ang, 2005).

0: start point, t: end point, C: carbon dioxide emissions, E: energy usage, G: GDP, P: population

$$\Delta C = C_t - C_0 = \frac{C_t - C_0}{\ln(C_t) - \ln(C_0)} \times (\ln(C_t) - \ln(C_0))$$

$$= \frac{C_t - C_0}{\ln(C_t) - \ln(C_0)} \times [\ln(\frac{C_t}{E_t} \times \frac{E_0}{C_0}) + \ln(\frac{E_t}{G_t} \times \frac{G_0}{E_0}) + \ln(\frac{G_t}{P_t} \times \frac{P_0}{G_0}) + \ln(\frac{P_t}{P_0})]$$

Change in carbon dioxide emissions (A) =
(Change in (carbon dioxide emissions/energy supply): B)
x (change in (energy supply/GDP): C) x (change in (GDP/population): D)
x ((Population change): E)
Simply put, the identity is A = B x C x D x E.

Item A is the change in carbon dioxide emissions from 0 to t. Item B is the change in carbon intensity. Carbon intensity considers that even if the amount of energy used is the same, the amount of carbon dioxide varies depending on the type of fossil fuel, such as coal, oil, or gas. Therefore, since carbon dioxide emissions vary depending on what energy source is used, it is an indicator of the change in carbon dioxide emissions per unit of energy supply. Item C is called Energy Intensity. The concept of energy intensity is as follows. It represents the amount of energy input to produce one unit of goods or services expressed as GDP, converted into monetary currency values. For example, to compare the energy intensity of each country, it represents the amount of energy input to produce 1$ GDP expressed in dollars, a common currency unit. If this indicator is relatively low, it can be interpreted as using energy more efficiently because it means that an economy uses less energy in the production process and produces one unit of GDP. Item D, per capita national income is mainly used as an indicator of how much each economy produced. It is a factor that indicates changes in the production of an economy, meaning that changes in national income per capita expressed in dollars can be a factor in changes in carbon dioxide emissions. Item E refers to the change in population, which generally indicates that the population of each country is increasing. Therefore, population factors are generally factors that increase carbon dioxide emissions.

Economic decomposition analysis produces different results depending on the scenario results, and major factors appear differently.

3.2.1. BAU scenario

[Figure 18] shows the decomposition analysis (2020-2050) by region under the BAU scenario. In general, economic growth contributes to greenhouse gas emissions

significantly, and energy intensity and carbon intensity contribute to reducing greenhouse gas emissions. Under the BAU scenario, the improvement of energy intensity is a relatively important factor for constraining greenhouse gas emissions in many regions. This figure indicates that there are huge regional variations, so it is important to consider the regional characteristics.

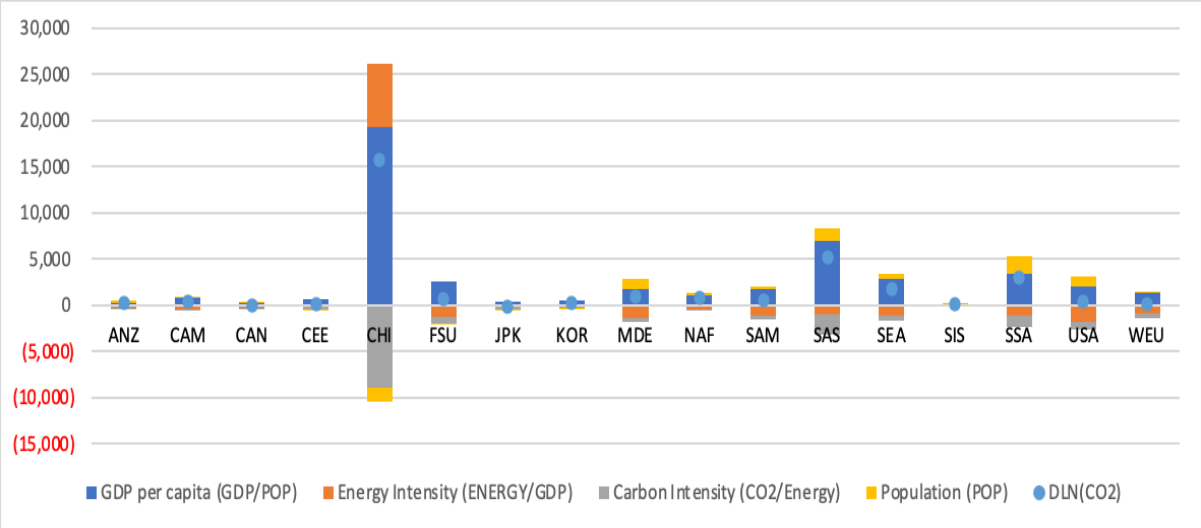


Figure 18. Decomposition Analysis (2020-2050) by Region under BAU scenario

In the BAU scenario, energy intensity is a very important factor in reducing greenhouse gases between 2020 and 2030 in Korea. In other words, energy use was reduced to produce one unit of GDP, and for this reason, it had a significant impact on the country's greenhouse gas reduction during the same period. The increase in GHG emissions in Korea is consistently due to the increase in economic activity (GDP per capita). Population factors and carbon intensity factors are also contributing factors to the decrease in GHG emissions during the same period. (See [Figure 19])

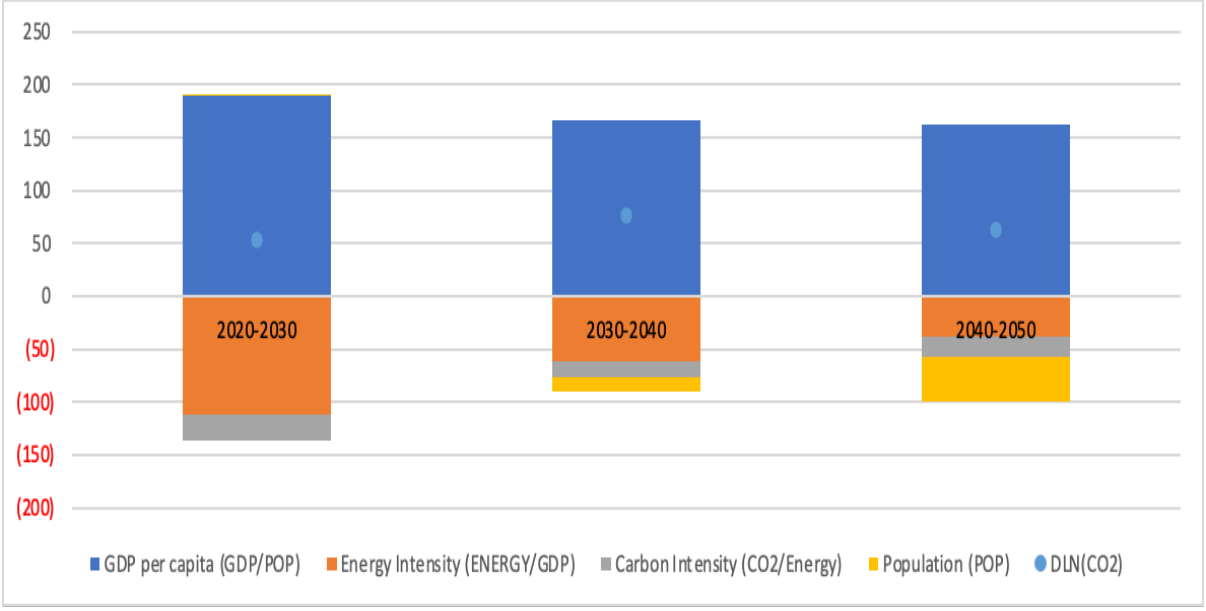


Figure 19. Decomposition Analysis under BAU scenario

3.2.2. CPrice scenario

By region, the introduction of carbon prices can contribute to reducing a significant amount of greenhouse gas emissions globally. Compared to the previous scenario, the contribution of the carbon intensity in constraining greenhouse gas emissions has noticeably increased in many regions. In addition, the energy intensity continues to play an important role in constraining greenhouse gas emissions.

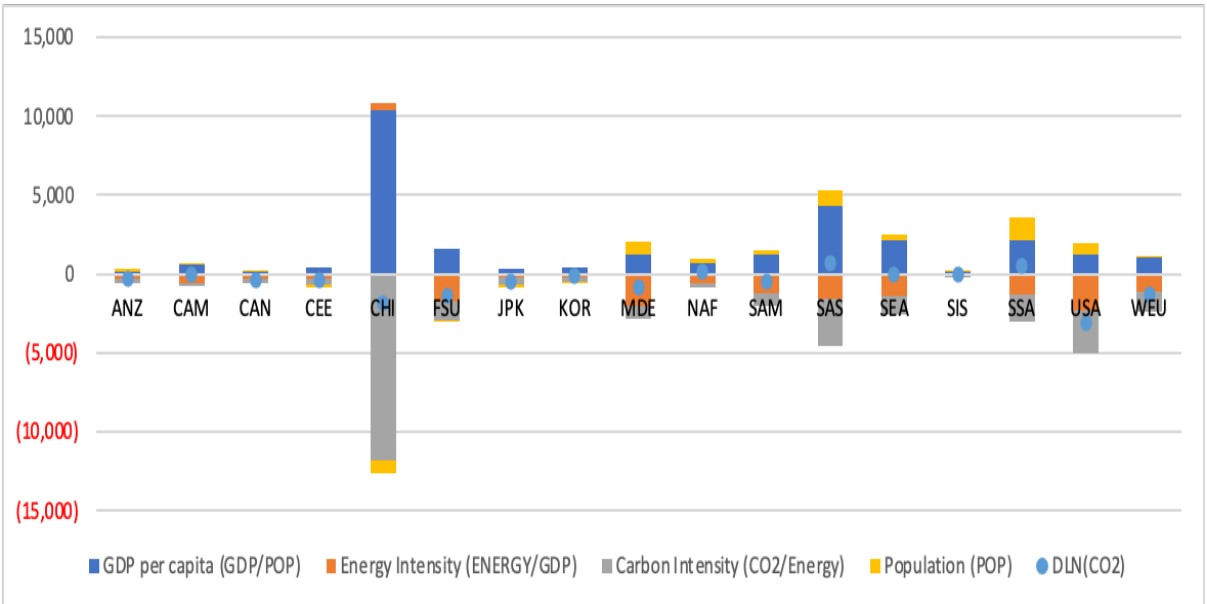


Figure 20. Decomposition Analysis (2020-2050) by Region under CPrice scenario

For Korea, contrary to the BAU scenario, the CPrice scenario results that achieving GHG mitigation depends on whether energy intensity is improved. Changing the industrial structure to a low-carbon type or reducing energy intensity by improving the efficiency of energy use is a major factor in reducing GHG emissions. (See [Figure 21].) In the NZ scenario, the reduction of GHG depends on the climate policy of Korea; whether to implement the policy domestically or implement part of the policy through the international carbon market is the factor for policy makers to determine. Since the introduction of the carbon price to trigger the change of energy mix to lower emissions, how to design the emission trading scheme or carbon tax will affect the carbon intensity factor. The increase in greenhouse gases due to economic growth is an inevitable factor, and population factors are also leading to a decrease in greenhouse gases regardless of the scenario. It is worth noting that to note that during 2040-2050, the net GHG emissions under this scenario are almost zero mainly due to the negative contribution of the carbon intensity and population growth are almost the same as the positive contribution of the GDP factor. Compared to the BAU scenario, the results of the Cprice scenario inevitably reduce the impact of economic factors such as per capita GDP. In other words, the policymakers should decide between economic policy and climate policy. Without remarkable technological breakthroughs, it is not easy to achieve economic prosperity and stabilize global temperatures. This common dilemma is also shown as we analyze the case of Korea.

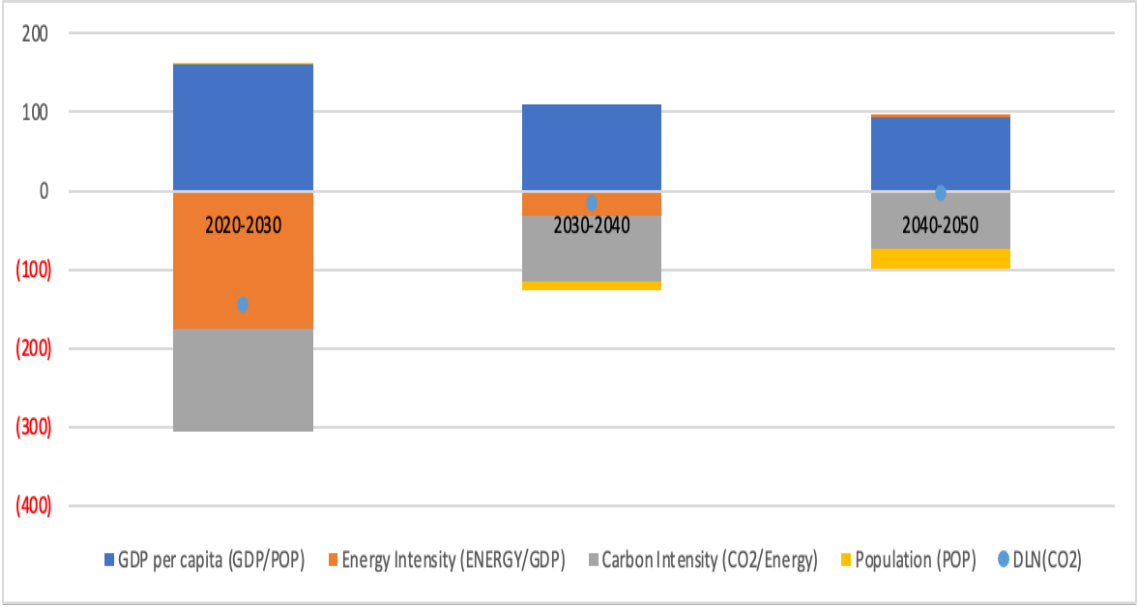


Figure 21. Decomposition Analysis under CPrice Scenario

3.2.3. LED scenario

As shown in the previous section, the results indicate that the LED scenario can reduce the economic losses from the introduction of carbon pricing. The result here is reflected in the decomposition analysis. The contribution of economic growth in increasing greenhouse gas emissions under the LED scenario is higher than that under the CPrice scenario. In both LED and CPrice scenarios, the results indicate that the introduction of carbon pricing and low energy demand measures can significantly improve carbon intensity and energy intensity.

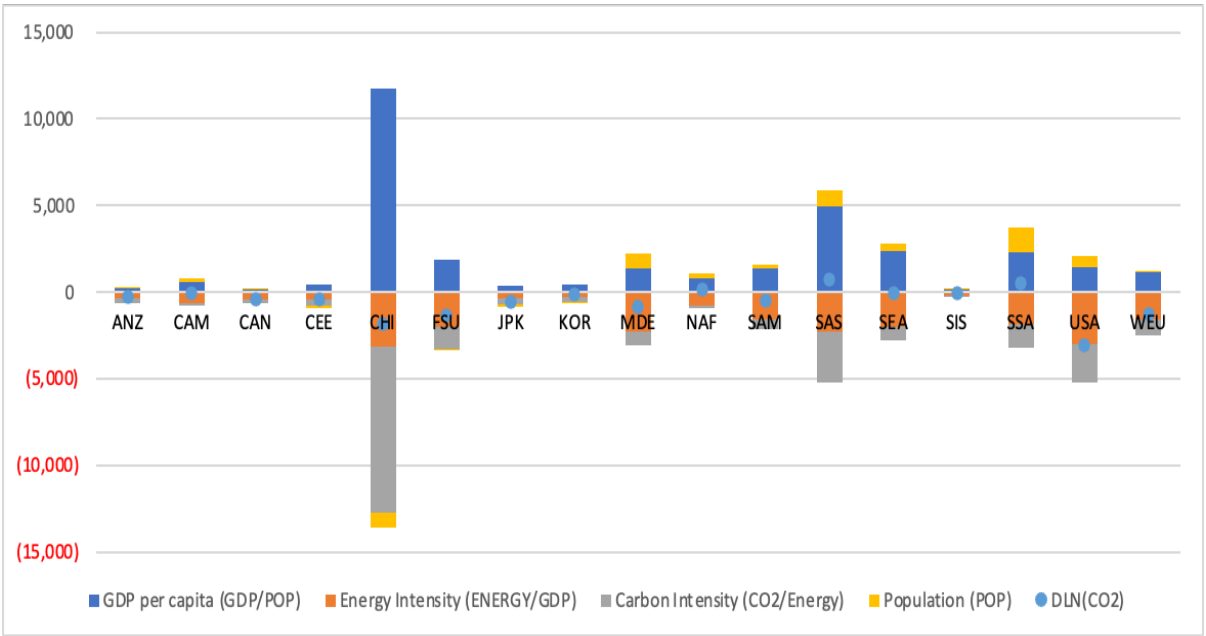


Figure 22. Decomposition Analysis (2020-2050) by region under LED Scenario

For Korea, the LED scenario's results highlight that the energy intensity improvement at the early period of the simulation period plays a pivotal role in reducing GHG emissions. Under this scenario, all sectors to use energy are assumed to improve the energy intensity. Also, the impact of low carbon policy results in a negative impact on carbon intensity. Compared to the BAU scenario, the LED scenario can bring positive economic gains, as shown in the previous section, while the CPrice scenario can bring economic losses. Thus, the contribution of GDP per capita is higher in the LED scenario compared to the CPrice scenario. As the greenhouse gas emissions of the two scenarios are the same, the energy intensity and carbon intensity have higher

negative impacts in the LED scenario compared to the CPrice scenario. LED Scenario can contribute to resolving the common dilemma between economic and climate policy discussed in the previous scenario.

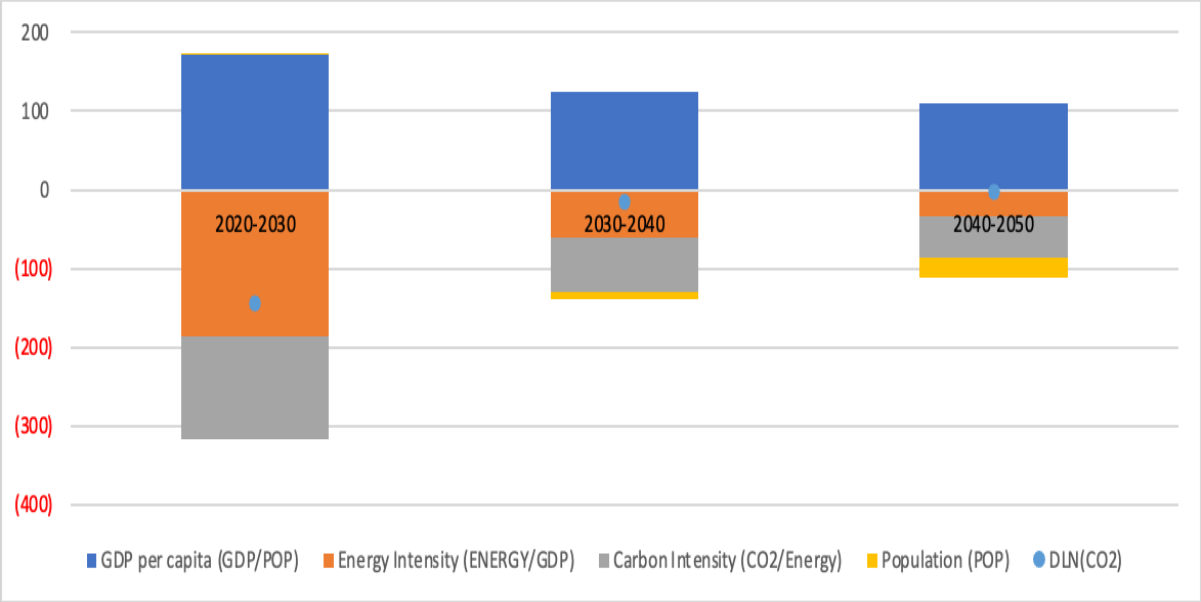


Figure 23. Decomposition Analysis under LED Scenario

3.3. Conclusion

This section analyzes the structural decomposition analysis based on the results from the global CGE analysis in the previous section. The study selects three scenarios, which are BAU with changes in cooling and heating energy demand (BAU), Carbon pricing (CPrice), and Low Energy Demand (LED) scenarios. In this section's BAU scenario is equivalent to the EXP scenario in the previous section for consistency. All three scenarios consider the changes in cooling and heating energy demand.

For structural decomposition, the Kaya identity decomposes the carbon dioxide emissions into four factors (carbon intensity of energy, energy intensity, GDP per capita, and population), and the study adopts the LMDI approach for decomposition analysis.

The BAU scenario indicates that economic growth contributes to greenhouse gas emissions in Korea, and population and energy intensity can be factors for reducing greenhouse gas emissions. As the Korean population starts to decline in the 2030s, the population degrowth can contribute to reducing greenhouse gas emissions in

Korea. In the CPrice scenario, the introduction of carbon prices can reduce greenhouse gas emissions, and the energy intensity and carbon intensity can contribute to reducing greenhouse gas emissions. While the introduction of carbon pricing can reduce greenhouse gas emissions in Korea, this may cause economic losses compared to the BAU scenario. It brings some challenges to the policymakers in keeping a balance between climate policy for reducing greenhouse gas emissions and economic policy for boosting economic growth. In the LED scenario, the result suggests that the low energy demand measures can provide some support to keeping such a balance. While the contribution of economic growth (GDP per capita) in greenhouse gas emissions is higher in the LED Scenario compared to the CPrice scenario, a higher contribution of energy intensity in reducing greenhouse gas emissions in the LED scenario helps to keep the same level of greenhouse gas emissions as the CPrice scenario. This implies that the LED scenario has some potential for facilitating the Net Zero transition.

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A Final Comparison of the EMF 37 and EDITS Projects: Objectives, Execution And Results

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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

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and water pollutants that were then slowly recognized to be quite detrimental to human health and well-being. In addition, by the turn of the last century, concern about climate change had increased to the point that the negative impact of increased fossil fuel use on social impacts of climate changes on economic and social well-being became a major cause for concern and policy attention. Although this was widely understood in the scientific community by the late 1990s, it has only been over the last ten years that increases in extreme weather events can be attributed with some degree of certainty to climate change and this has captured significant media and public attention. This has led to calls for much more aggressive reductions in greenhouse gas (GHG) emissions (IPCC 2018), which creates a huge incentive to consider a much greater focus on energy demand measures to reduce GHG emissions through end-use demand reductions, as well as fuel switching and technological change on the energy demand side of energy systems around the world. The argument here is that although these policies and measures might be costly to society, especially if some important adjustment costs are included, a range of demand side adjustments seem likely to be much less expensive than many of the supply side options that have been projected to be "least costly" on the margin-meaning that not all energy demand side options will be less expensive, but many of them are likely to be so and, are, therefore, worthy of much greater attention than has occurred so far. The combined environmental, security, robustness and resilience benefits of reductions in energy demand may, therefore, in many cases be accompanied by economic benefits as well.

This story line was pursued previously using the experiences in the initial stages of the EDITS and 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 objectives and a narrower geographical scope. In this report we focus on comparing the initial EMF 37 scenario results with the EDITS High with Low (HwL) scenario target scenario.

We then close with some updated recommendations from these conclusions for the future of EDITS and EMF 37 and similar work on scenarios that put more emphasis on demand side technologies, behaviors, and policies.

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

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.

[1] This section draws heavily and quotes freely from the High-with-Low narrative document (Grubler. et al., 2022).

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

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).

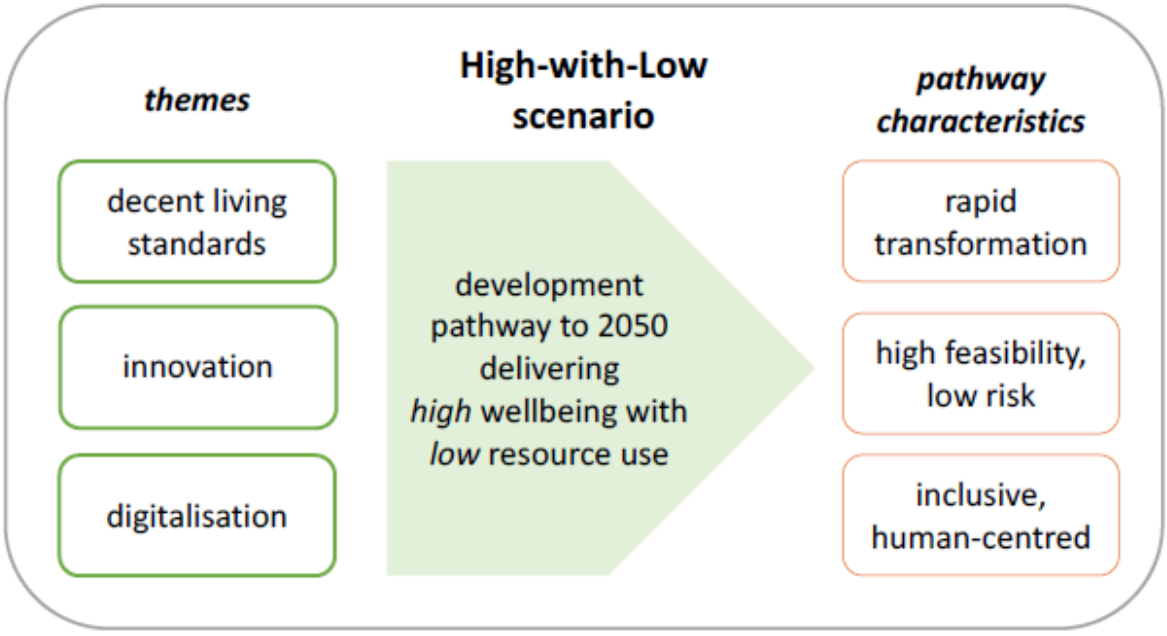

Figure 1. Three Main Themes In The High-With-Low Scenario, And Characteristics Of The Resulting Development Pathway To 2050.

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

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threat of terrorism, conflict and migration (Hallegatte and Rosenberg2017, Hallegatte, Fay et al. 2018, Bastia and Skeldon 2020).

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.

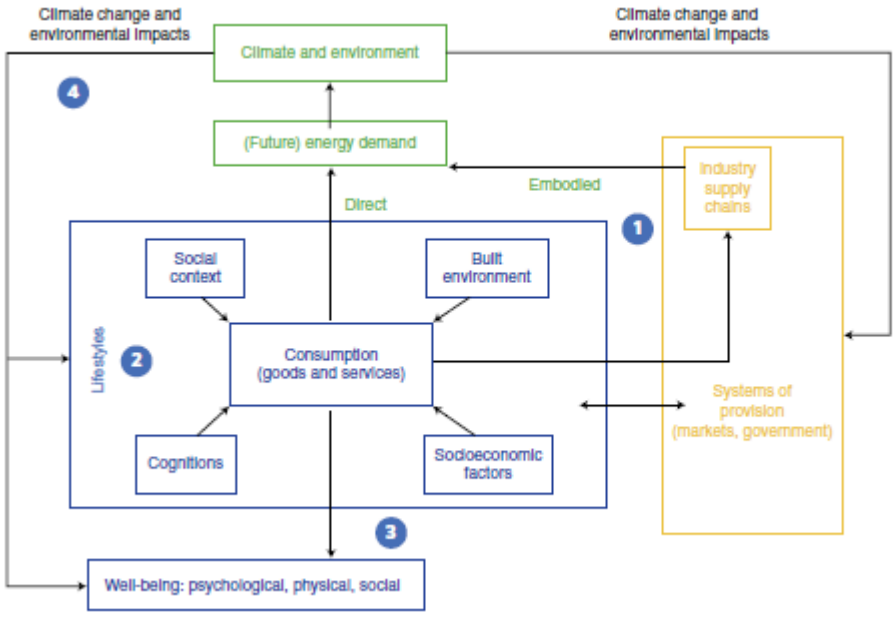

Figure 2. Conceptual Linkages Between Human Well-Being and Climate Change Through Consumption and Its Derived Energy Demand: (1) Energy Demand Modeling and Household Heterogeneity; (2) Lifestyles And Consumption; (3) Consumption And Well-Being; (4) Equity And Well-Being. The Colored Boxes Differentiate 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 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-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

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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.

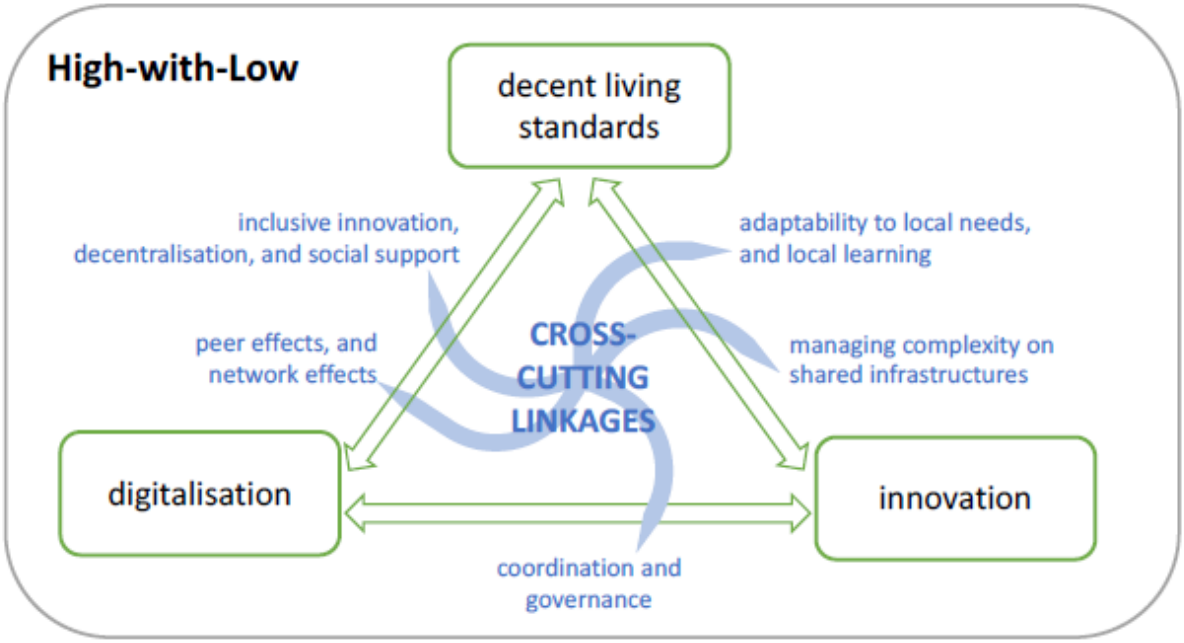

Figure 3. Cross-Cutting Linkages Between The Three Themes Of The High-With-Low Scenario.

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).

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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. 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.

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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), 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 optimized 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 program of transformation towards High-with-Low goals.

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;
- 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 behaviors. 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.

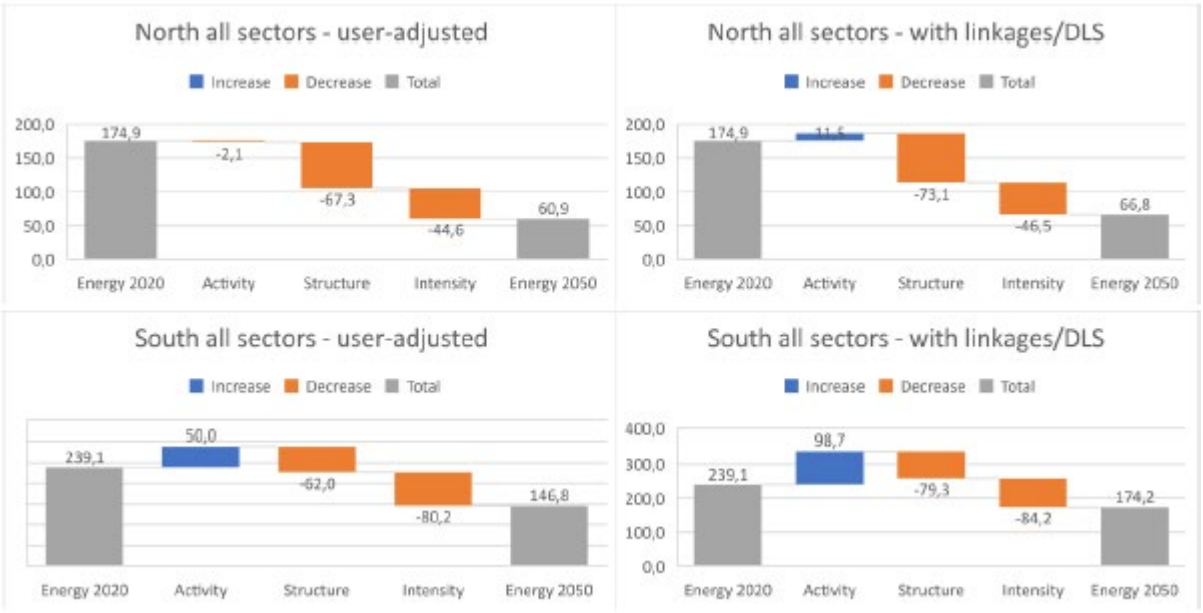

Figure 4. Changes in Final Energy Use From 2020 to 2050 Decomposed into Activity, Structure, and Intensity Components in a High-With-Low Scenario, Distinguishing: (1) Global North (Upper Panels) And Global South (Lower Panels); (2) User-Adjusted Global LED Scenario (Left Panels) And Inter-Sectoral Linkages 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.

<u>Ensuring High-with-Low modelling is consistent with activity levels and energy requirements to provide decent living standards for all</u>

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

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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).

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.

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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 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

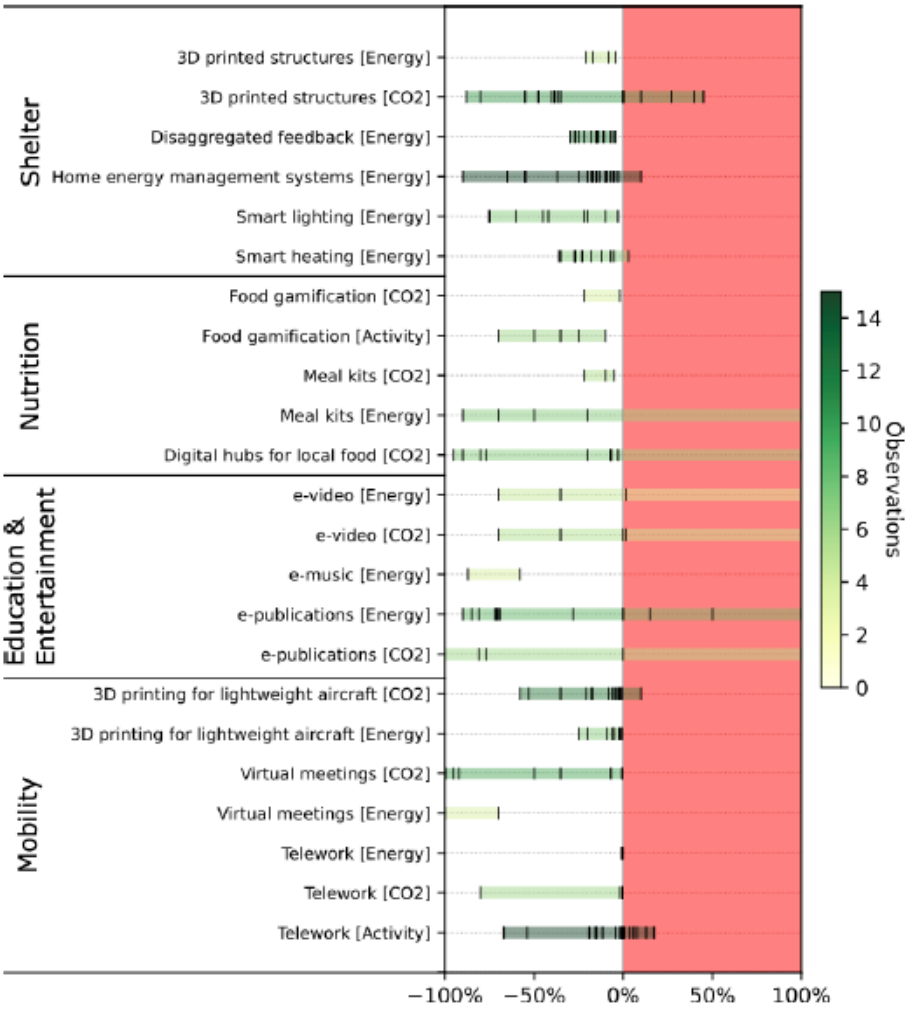

Figure 5. Studies assessing net changes in CO2 emissions, energy use, and activity levels indicate mitigation potentials for numerous end user-oriented digitalization solutions, but also risk of increased emissions due to inefficient substitutions, induced demand, and rebound effects. 90 studies were assessed with 207 observations (indicated by vertical bars) including those based on empirical research, attributional and consequential life-cycle assessments.

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).

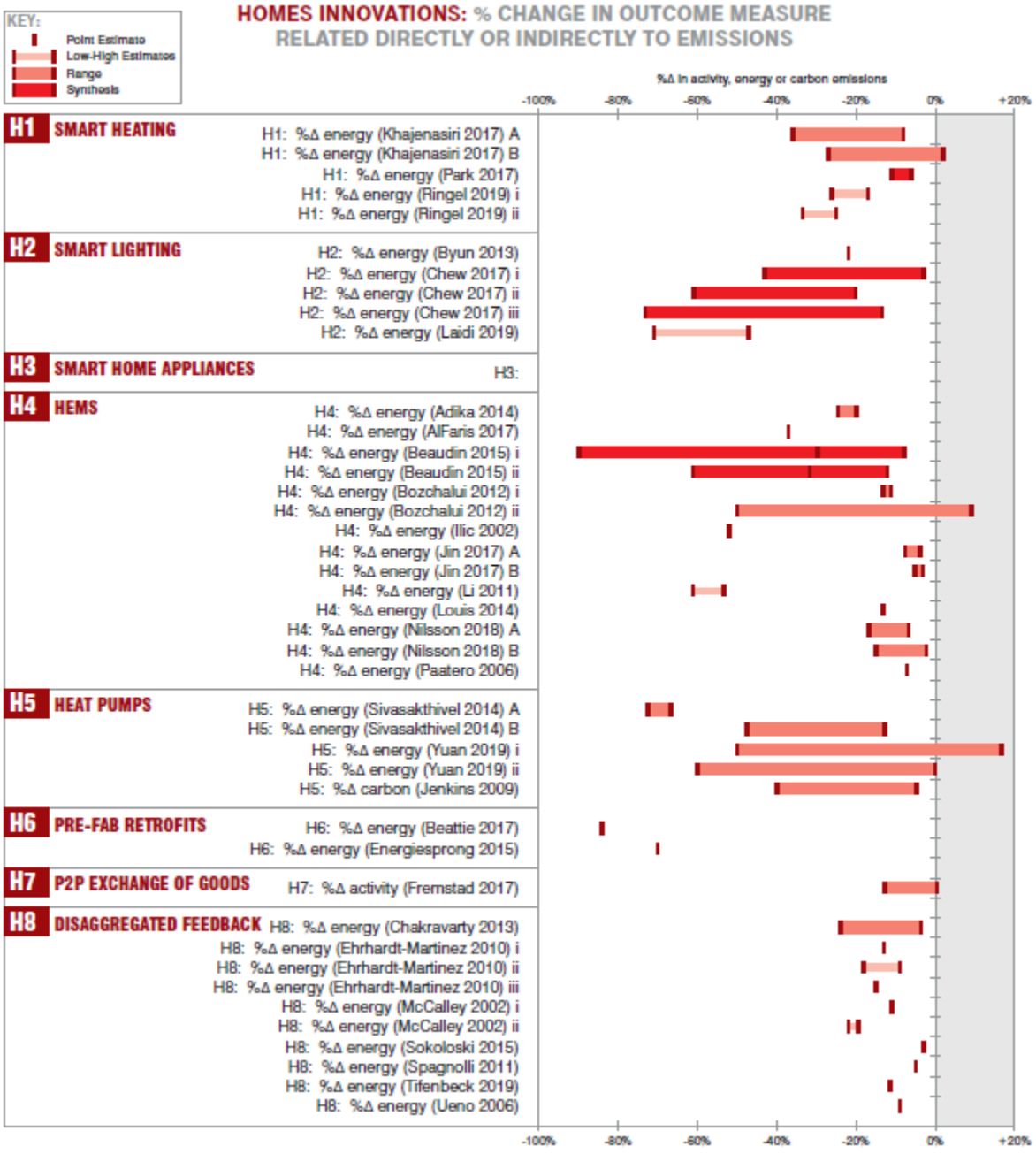

Figure 6. Synthesis of Estimates of Net Changes In C02 Emissions, Energy Use And Activity Levels as an Indicator of Mitigation Potentials From Digitally-Enabled Led Technologies In The Home.
Note: Similar Estimates Are Available For Digital Mobility And Food Innovations. Source: (Wilson, Kerr et al., 2020).

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 has been 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 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 meetings of the full working group that started in October 2020 and will continue through early 2024.

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:

[2] This section draws heavily and quotes freely from Eenergy Modeling Forum (2022).

- To what extent can the transportation, buildings, and industrial sectors be electrified, particularly in the context of policies to achieve deep decarbonization and "net-zero" emissions? How might technological and behavioral change and decarbonization efforts alter the extent of electrification?
    - Beyond decarbonization efforts, what are the key drivers of electrification in the transportation, buildings, and industrial sectors?
    - How might the availability of other decarbonization options such as carbon management and low-carbon fuel sources (e.g., biofuels or hydrogen in various forms) compete with electricity to moderate the extent of electrification?
- What are the implications of high electrification scenarios on the energy system and economic and environmental outcomes in North America in reference projections and across a range of decarbonization scenarios?
- How does technological change in the power sector shape electrification pathways?

Importantly, the study is designed to engage all energy and economy-wide models as well as sectoral and technology experts forming study groups focused on transportation, industry, buildings and carbon management.

The study description and design are presented in four sections below:

- Study Structure and Process i.e., types of models and rounds of the study
- Overview of the Scenarios i.e., scenario matrices and illustrative sensitivity examples
- Scenario Details and Discussion i.e., detailed specifications
- Reporting and Submissions i.e., reporting template development and submission process

Study Structure and Process

To address the questions above, the EMF 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.

[3] As used here, economywide includes both general and partial equilibrium models with comprehensive energy sector coverage.

The process went through a beta and three 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, 2, and 3.

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-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 study schedule included roughly monthly virtual meetings that were 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).

Table 6 presents the Round 2/3 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 were 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).

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

[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.

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 6
EMF 37 Round 2 Final Scenario Matrix

Short Scenario Name	Overall Scenarios				No Target	Net 0 by 2050	Net 0 by 2060	Net 0 by 2080	Net 0 GHG by 2050
	CMSG	Trans	Ind	Bldg					
Ref Tech	Ref	Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R2	0by60.Ref.R2	0by80.Ref.R2	DGHGby50.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	DGHGDby50.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			No Target	Net 0 by 2050	Net 0 by 2060	Net 0 by 2080
	CCS	H2 Prod.	DAC				
Ref Tech	Ref	Ref	Ref	NT.Ref.R1	0by50.Ref.R2	0by50.Ref.R2	0by50.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			No Target	Net 0 by 2050
	Technology Adv. Tech	Policy Policy Enlbmt	Preference Behv. Chg.		
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

Short Scenario Name	Industry Technology				No Target	Net 0 by 2050
	EE	Mat. Eff.	RE/H2/CCUS	Ind. Elec		
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		Standards Bldg Policy		No Target	Net 0 by 2050
	Elec	EE	Elec	EE		
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

Reference Scenario
Model Default Policy Scenario
All Advanced - Interaction Scenario
All Advanced - Study Group Scenario
Study Group Scenario
Optional Scenario

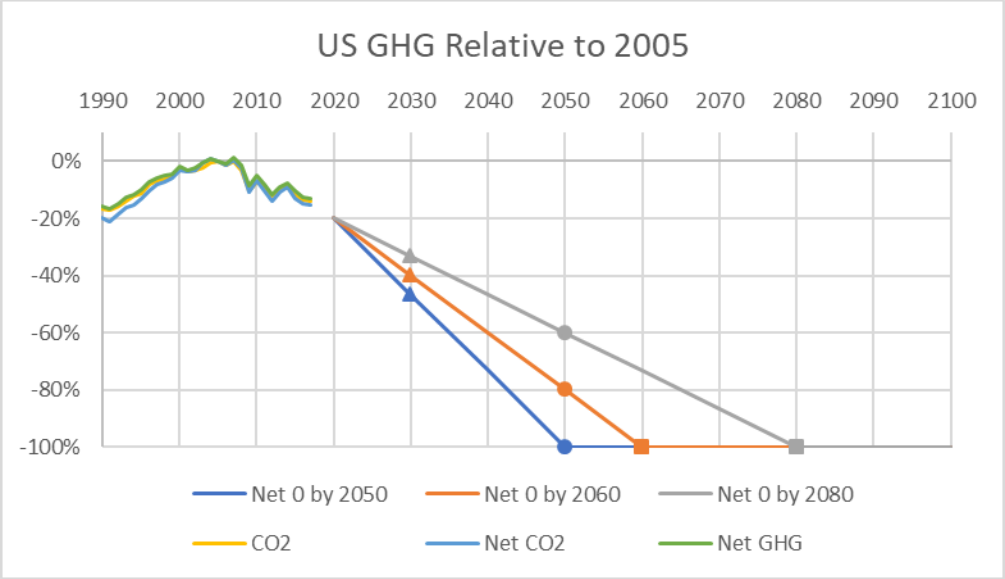

Figure 7. Illustrative decarbonization pathways for the US (Note: Canada and Mexico will follow similar straight-line reduction trajectories from 2020 to net zero).

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 7.

A more detailed sectoral breakdown of the US GHG Inventory is presented in Table 8. Note that emissions from biomass consumption (e.g., wood, ethanol and biodiesel) are embedded with the LULUCF category.

While the emissions pathways are specified as CO2 only, models should assume that the resulting carbon price or shadow price on carbon should also be applied to non-CO2 greenhouse gases. In addition, we include a net-zero GHG by 2050 sensitivity scenario to shed additional light on the differences between net-zero CO2 and net-zero GHG targets.

Banking and Borrowing: No banking or borrowing is allowed in meeting the reduction targets. While allowing full flexibility with banking and borrowing may be more efficient, it would obscure some of the key issues we want to explore in this study. First, we are interested in what the net-zero energy system and economy look like, and banking would allow models to avoid meeting that target. Second,

we are also interested in the 2030 results along the path towards net-zero. With banking and borrowing, and carbon prices following a Hotelling path, the near-term results and the initial carbon price are driven by long-term technology assumptions

Additional Assumptions

International Policy Outside of North America: The focus of this study is on high electrification scenarios for North America under different rates of decarbonization. To minimize the trade effects in global models or models that represent international trade, assume that all regions face the same carbon price as found in North America.

Offsets: These scenarios assume no international or domestic offsets or tax credits of any kind.

Reporting and Submissions

We used 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 7

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**

Table 8

Summary of US CO_2 emissions inventory in 2005 and 2018 (Mt CO_2e)

INCLUDED SOURCES		
	Inventory	
Gas/Source	**2005**	**2018**
CO2 (gross)	6,132	5,425
Fossil Fuel Combustion	5,741	5,032
Transportation	1,856	1,821
Electric Power	2,400	1,753
Industrial	850	833
Residential	358	337
Commercial	227	247
U.S. Territories	50	41
Non-Energy Use of Fuels	140	135
Industrial Process	252	258
Iron and Steel Production & Metallurgical Coke Production	70	43
Cement Production	46	40
Petroleum Systems	12	37
Natural Gas Systems	25	35
Petrochemical Production	27	29
Other	70	74
Land Use, Land-Use Change, and Forestry[a] (Sink)	-815	-774
Net CO2 Emissions (Sources and Sinks)	5,317	4,651
EMBEDDED or EXCLUDED		
Wood Biomass, Ethanol, and Biodiesel Consumption (embedded in LULUCF sink) [a]	231	329
Non-CO_2 GHG (excluded)	1,260	1,252

Source:Excerpt from US EPA GHG Inventory Report, Table ES-2.

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

Reporting variables and template: A list of reporting variables with common names and definitions will be developed and agreed upon before the beta round. The variable list developed by the Integrated Assessment Modeling Consortium will serve as a starting point. New variables will need to be added to

cover the detailed, sector-specific information for this study as well as variables that may need to be passed back-and-forth between models.

Reporting template and data repository: Modelers will upload results in an Excel spreadsheet format to a data repository hosted by IIASA. The repository compiles all of the results into a single database and can perform submission checks of the data.

Modelers' Choice Scenario Options

The discussion above notes several potential modelers' choice options. The analysis, interpretation, and documentation of modeler's choice scenarios may require reporting variables that are not contained in the standard database template. The best way to report non-standard variables is to enter the custom data into an existing, unused variable and note the new definition of the variable in the 'comments' tab of the data template.

Modeler's choice scenarios may address a variety of other areas such as additional alternate technological dimensions or the inclusion of non-CO_2 GHG's under decarbonization targets.

Study Groups, Cross-Cutting Paper Writing Teams and Individual Modeling Team Papers

Very initial recruiting of working group members started in summer and early fall 2019 with a scoping meeting taking place September 26-27, 2019 in Washington DC even as EMF 33, EMF 34, EMF 35, and EMF 36 were still in progress. After a scoping meeting, the group decided on a set of preliminary questions to be addressed within the model inter-comparison study; sketched out a number of tentative common scenarios for the modeling teams to run to address those questions; formed initial study groups to go deeper into some of the technical and institutional issues that arose; and set a schedule for submission, reporting, and debugging model results for the first-round scenarios before a first full working group meeting. By early 2020, an initial Steering Committee to help guide the overall progress of the study was established by PI John Weyant. This group interacted with various advisors and leading modeling and sectoral analysis experts to collect ideas on what the study should focus on and how it should be organized, especially in the Covid-19 environment in which the process was by then operating.

That meeting was to have taken place in Washington DC on May 21-22, 2020 in conjunction with a presentation of the EMF 34 results on the afternoon of May 20th. These meetings were moved online and broken up into more manageable monthly online meetings starting in early 2020 due to the Coronavirus pandemic. During the period from February 2020 until September 2020 the recruiting and establishment of four study groups was completed. These groups were: (1) Carbon Management; (2) Transportation Energy Use; (3) Building Energy Use; and (4) Industrial Energy Use, as well as the recruitment of a couple dozen US and Canadian energy systems modeling groups. These groups were then all brought together for monthly three- to four-hour online meetings starting in November 2020 with the steering committee vetting an initial plan for how to proceed in November and December of 2020, with the four study groups organizing the agendas for the January-April 2021 meetings around their interests. During this period a small group of "Beta" round scenarios for the energy systems models were designed to familiarize everyone with the data management system being used and the variable and scenario definitions included in the results reporting template. The next few monthly meetings were used to review these initial results and develop a larger group of more integrated "Round #1" scenarios with input from the energy systems modelers and the leaders of the four study groups.

Results for these scenarios were reviewed by the whole working group in a series of meetings from the fall of 2021 through the first half of 2022. At the same time the four study groups convened their own monthly meeting to develop and push forward their own work plans and add energy systems modelers who wanted to add more depth in the representation of these sectors. This process has greatly helped both the systems modelers and the study groups pursue their objectives. This process was then repeated in the summer and fall of 2022 (again through online meetings) with a goal of developing a set of round #2 scenarios by July of 2022 and reviewing both overview and study group specific scenarios during the fall of 2022. At the same time, a number of cross-cutting writing teams were organized to review the results more comprehensively and in greater detail to draw insights for model, as well as policy and strategy development in greater detail. At present, eight cross-cut teams (including about a dozen experts per team) have been established – (1) hydrogen, (2) equity, (3) ancillary air quality impacts, (4) a parallel European study, (5) biofuels, (6) trade, (7) electricity markets, and (8) a policy overview – and are meeting on their own in between full working group meetings in the

following areas: electricity markets, hydrogen, bio-fuels, trade, ancillary impacts, and distributional and equity outcomes. Finally, a number of individual modeling teams are preparing papers highlighting unique insights developed from their running of the study scenarios and others they find particularly interesting.

During the first half of 2023, this process was repeated for a third time, with the goal of producing papers summarizing the work of the four study groups while updating the analyses of the overview scenarios and further pursuing the objectives of the cross-cut writing teams. Then, during the second half of 2023 this process is being repeated with a focus on completing papers by the cross-cut writing teams by early 2024. In addition, it is likely that some of the study groups and cross-cut teams will produce additional papers, and so far a dozen of the 20 energy systems modeling teams participating in the study will produce papers based on their own unique perspectives and insights they were able to draw beyond what is in the group and cross cut papers.

A final summary report on the work of the group and set of supporting study group, cross-cut papers, and modelers papers will be assembled online in *Energy and Climate Change* and briefings of the findings to interested parties are being organized during the first half of 2024.

Preliminary Results

Overview results from the first stage of the study were published in the first contribution to a special issue of the Journal *Energy and Climate Policy*[5]. That journal will allow EMF to add papers summarizing more updated and more detailed results being prepared by study participants online on a broad range of cross-cutting issues (listed above) during late 2023 and early 2024 as they become available (the papers currently in the publication pipeline are listed in Table E-1 in Appendix F).

The complete EMF 37 overview paper is (Browning, et al, 2024). Here we summarize the results of the study that are most relevant to the EDITS goals and objectives. Note that some of the most relevant results are including in the supplementary material for the publication as will be

[5] Net-Zero CO2 by 2050 Scenarios for the United States in the Energy Modeling Forum 37 Study. Energy and climate change Browning, M., McFarland, J., Bistline, J., Boyd, G., Muratori, M., Binsted, M., Harris, C., Mai, T., Blanford, G., Edmonds, J., Fawcett, A. A., Kaplan, O., Weyant, J. 2023; 4: 1-13

described later in this section of the present report.

Scenarios

The initial EMF 37 report focused primarily on results from three core study scenarios: (1) A *Reference scenario* which assumes no new climate policy after early 2022; (2) A *Net Zero scenario* which considers an emission reduction pathway specified as a linear CO_2 emission reduction from 2020 to net-zero emissions by 2050, and (3) A *Net Zero+ scenario* which uses the same linear emissions reduction pathway as the Net Zero scenario, but with optimistic assumptions regarding the potential for electrification and decarbonization across the buildings, industry, transportation, and carbon management sectors.

Models

Results from 16 models for the three core scenarios were included in the initial overview paper for the study[6]. this paper span a spectrum of spatial, sectoral, and technological detail; partial and general equilibrium approaches; myopic and perfect foresight; as well as optimization and simulation frameworks. The table 9 provides a summary of model characteristics. For additional details, refer to the model documentation linked to Browning, e al., 2024) and published papers on the models cited in the Supplementary material for the overview paper and repeated here in Table F-1 in Appendix F.

[6] Results from several addtitional models are being including in the papers now under preparation or review at the journal.

Table 9

Summary characteristics of model participating in EMF 37
(This is Table 2 in Browning., et al. (2024))

Model Name (Institution)	Spatial Resolution	Gas Coverage	Equilibrium approach & Foresight	Base-End Years; Timestep; Technology Choice	Carbon Management Options	Electric Sector	Buildings	Industry	Transport
ADAGE RTI International)	US+7 global regions	CO_2 & non-CO_2	General; Myopic	2010–2050; 5-year time steps; CES	DAC, Biofuels	11 technologies	Residential: 3 end-use Commercial: aggregated with other sectors	13 energy 24 non-energy sectors	8 modes, 1 vehicle class, power train options
AnyMOD (TU Berlin)	US, Canada, and Mexico	CO_2 only	Partial; Perfect	2020–2050; 5-year time steps; LP	BECCS, DAC, H_2	32 generation technologies, 4 storage technologies, 59 regions (49 states for the US)	Single building type	single industry sector	Passenger: 3 modes, Freight: 3 modes, 18 class/ powertrains
EC-MSMR (Environment and Climate Change Canada)	Canada, Mexico, US + 13 other regions	CO_2 & non-CO_2	General; Myopic	2014–2050, 5-year time steps; CES	BECCS (Electricity only), DAC, Green H_2, Biofuels, Renewable Natural Gas	13 technologies including backstops, 17 regions	Residential: included in households ommercial: single sector	4 energy 5 non-energy	2 modes (passenger included in household)
ENERGYpathways AND RIO (eVOLVED eNERGY)	27 US regions corresponding to EPA eGRID (aggregation of zones in Alaska and Hawaii)	CO_2 & non-CO_2	Partial; Perfect	2021–2050; 5-year time step; Mixed; LP in electricity and fuel, logit in end-use	BECCS, DAC, H_2, H_2 storage, Biofuels, Synthetic Gas & Liquids, Ammonia (38 fuel conversion/ storage technologies)	27 regions; 62 technologies; 960 time periods (40 day samples w 24 sequential hours)	Residential - 16 end-uses x 3 building types; Commercial - 12 end-uses x 11 building types	20 industrial subsectors x 8 service categories (heat, hvac, lighting, machine drives, refrigeration, support, transport, and other)	14 modes, 44 class/ powertrains
EPA-TIMES USEPA/ORD)	9 US regions	CO_2 & non-CO_2	Partial; Perfect	2010–2050, 5-year time steps; LP	BECCS (Electricity only), DAC, H_2, Biofuels	24 technologies; 9 US regions	Residential: 7 end-uses Commercial: 9 end-uses	20 sectors	2 modes, Light-duty: 9 classes, 10 powertrains Heavy-duty: 9 classes, 10 powertrains
EPS (Energy Innovation)	US	CO_2 & non-CO_2	Partial; Myopic	2020–2050, 1-year time steps; Logit	DAC, H_2, Biofuels	16 technologies; 1 region	Residential: uban & rural Commercial: single 6 end-uses	25 manufacturing sectors (including energy)	6 modes, 2 classes, 7 power trains
FARM (USDA)	US, Canada + 11 other world regions	CO_2 only	General; Myopic	2011–2101, 5-year time steps; Mixed: Logit for electricity generation shares; CES otherwise	BECCS, Biofuels	10 technologies; 1 region	Residential: single Commercial: single	6 energy-intensive; 1 other industry	3 modes (land, air, water); Fuels for land include petroleum, biofuels, electricity

FARM (USDA)	US, Canada + 11 other world regions	CO_2 only	General; Myopic	2011–2101, 5-year time steps; Mixed: Logit for electricity generation shares; CES otherwise	BECCS, Biofuels	10 technologies; 1 region	Residential: single Commercial: single	6 energy-intensive; 1 other industry	3 modes (land, air, water); Fuels for land include petroleum, biofuels, electricity
FECM-NEMS & OP-NEMS (OnLocation)	US; subnational aggregation varies by submodule	CO_2 only	Partial; Near-perfect (electricity, liquid fuels), Myopic (demand)	2021–2050; 1-year time steps; Mixed: LP in power and liquid fuels; MIP for CO_2 pipeline and storage; Logit in demand models	BECCS (electricity only), DAC, CCS for ethanol, natural gas processing, H_2 in refineries and cement; liquid biofuels	24 new tech, 3 CCS retrofit techs, plant-level database for existing techs, and 25 NERC-based regions.	Residential: 3 types, 12 end-uses ommercial: 11 types, 10 end-uses 9 Census regions	15 manufacturing6 non-manufacturing plus refining 4 Census divisions.	8 modes, 16 LDV classes, commercial light trucks and 3 freight classes, 10 power trains
GCAM (PNNL)	Canada, Mexico, US, +29 other regions	CO_2 & non-CO_2	Partial; Myopic	2015–2100; 5-year time step; New investment: logit based on expected profitability;	BECCS (electricity, biofuels, H_2 with CCS), DAC, H_2 in end-use, liquid	23 technologies; 9 fuels; single market per region	Residential: US 14 end-use Commercial: US 10 end-use ROW end-use 3	6 manufacturing 3 non-manufacturing	Passenger: 6 modes, 4 classes, 11 power trains. Freight: 3 modes, 3 HDV classes,
gTech (Navius Research)	Canadian Provinces + US	CO_2 & non-CO_2	General; Myopic	2015–2050; 5-year time steps; CES	DAC, BECCS, H_2, Biofuels	16 technologies; 11 regions	Residential: 3 shell types, 11 end-uses Commercial: 6 shells types, 6 end-uses	34 non-energy industrial sectors 9 agriculture & forestry sectors 24 energy sectors	5 modes, 6 classes, 11 power trains
MARKAL-NETL (NETL)	9 US Census regions	CO_2 & non-CO_2	Partial; Perfect	2005–2075; 5-year time steps; LP	BECCS, DAC, H_2, Biofuels, Synthetic Gas & Liquids	45 technologies, 9 regions	Residential: 8 end-uses Commercial: 12 end-uses	7 non-energy, 9 industrial energy carriers	3 modes, 9 classes, 10 power trains
NATEM (Esmia Consultants)	13 Canadian regions; 9 US Census regions + CA, TX, NY; Mexico	CO_2 & non-CO_2	Partial; Perfect	2016–2060; 2- to 5-year time steps; LP	BECCS, DAC, H_2, Biofuels, Synthetic Gas & Liquids	US: 90 technologies, 12 regions	US Residential: 8 end-uses Commercial: 12 end-uses	7 non-energy 8 industrial energy carriers	6 modes, Passenger: 3 classes, 9 powertrains Commercial: 3 classes, 9 powertrains 15 fuels
TEMOA (North Carolina State University)	9 US regions	CO_2 only	Partial; Perfect	2020 to 2050; 5-year time steps; LP	BECCS (electricity only), DAC, H_2, Biofuels, Synthetic fuels	3 storage technologies; 15 generation technology types; 9 regions	Residential: 10 end-uses Commercial: 8 end-uses	2 sectors Manufacturing: 9 end-uses Non-manufacturing: 6 end-uses	6 modes, Passenger: 1 class, 4 powertrains Commercial: 2 classes
US-REGEN (EPRI)	16 US regions	CO_2 & non-CO_2	Partial; Perfect	2015–2050; 5-year time steps; Mixed; LP in electric and fuels sectors, logit in end-use sectors	BECCS, DAC, H_2, Biofuels, Synthetic Gas & Liquids, Ammonia	16 regions; 94 technologies; 120 representative hours / hourly dispatch	Residential & Commercial sectors 2 size categories plus vintages and climate zones 6 end-uses	37 non-energy sectors	36 vehicle classes/ powertrains
USREP-ReEDS (MIT-NREL)	USREP: 12 US regions ReEDS: 134 balancing areas	CO_2 & non-CO_2	General; Myopic	2017–2100; 5-year time steps; Mixed; CES in USREP; LP in ReEDS	BECCS (Electricity only), DAC, Biofuels	58 technologies 134 balancing areas (CONUS) 17 time slices	Residential & Commercial Production function with 3 fuels	5 energy 6 non-energy	2 modes, Passenger: 3 classes; Non-passenger is aggregated into a single sector

Notes: LP = linear program, CES = Constant Elasticity of Substitution, BECCS = biomass energy with carbon capture and sequestration, DAC = Direct Air Capture, H2 = hydrogen.
Additional model information (unique attributes, website, and references) may be found in Table SM1.

Emissions

Across net-zero scenarios, power sector emissions are reduced by no less than 57% from 2020 to 2050, ranging from 59 to 100% lower emissions than in the Reference scenario by 2050 (Fig. 8), though only one model meets the U.S. 2035 Net-Zero goal for electricity sector CO2

emissions (see SM1.3). By 2050 in the net-zero scenarios, there are few remaining residual emissions in the power sector (Fig. 8). Those residual power sector emissions are generally larger in the Net Zero+ scenario than in the Net Zero scenario. For about half of the models, reduction in power sector emissions in 2050 equals or surpasses the sum of the reductions across other energy sectors in the Net Zero scenario. With the addition of optimistic assumptions in the Net Zero+ scenario, buildings, industry, and transportation take up a greater percentage of emissions reductions. Three dynamics significantly contribute to these results: (1) optimistic assumptions in the Net Zero+ scenario lead to greater end-use emissions reductions, requiring less power sector mitigation to achieve net-zero, (2) optimistic assumptions lead to greater end-use electrification, which requires more output, and thus possibly greater emissions from the power sector, and (3) the Net Zero+ scenario projects increased availability and lower costs of carbon removal technologies that can offset unmitigated emissions. Residual emissions in the net-zero scenarios in transportation are larger than in other sectors for most models, followed

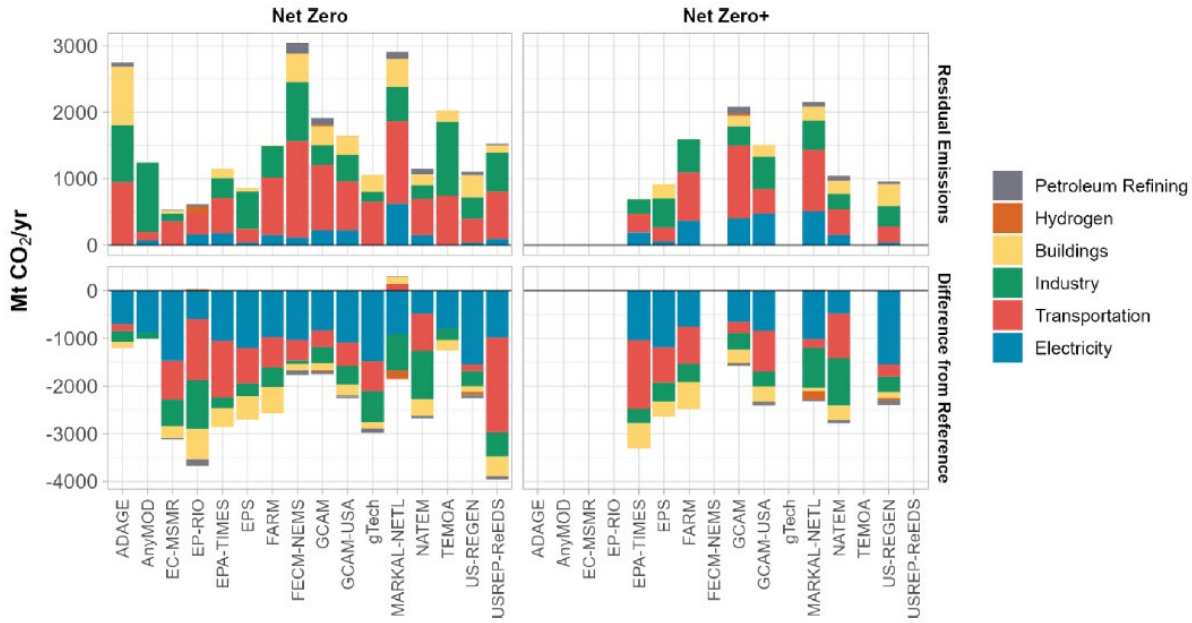

Fig. 8. (Figure 2 in Browning, et al., 2024) Sectoral CO2 Emissions for Net Zero Scenarios in 2050. The top panel stacked bars show residual sectoral emissions in the Net Zero and Net Zero+ scenarios. Transportation and industry have the largest variation in emissions between models. The lower panel stacked bars show the difference in sectoral emissions from the Reference scenario to the Net Zero and Net Zero+ scenarios. Most models show reductions in gross emissions across the buildings, industry, and transportation sectors, with the largest reduction in the power sector, as compared to the Reference scenario. See Figure 9 for difference between Net Zero and Net Zero+ residual emissions.

by industry and buildings emissions. Of the eight models that ran the Net Zero+ scenario, six show greater transportation emissions reductions than in the Net Zero scenario and four show greater industry and buildings emissions reductions than in the Net Zero scenario (see Fig. 9).

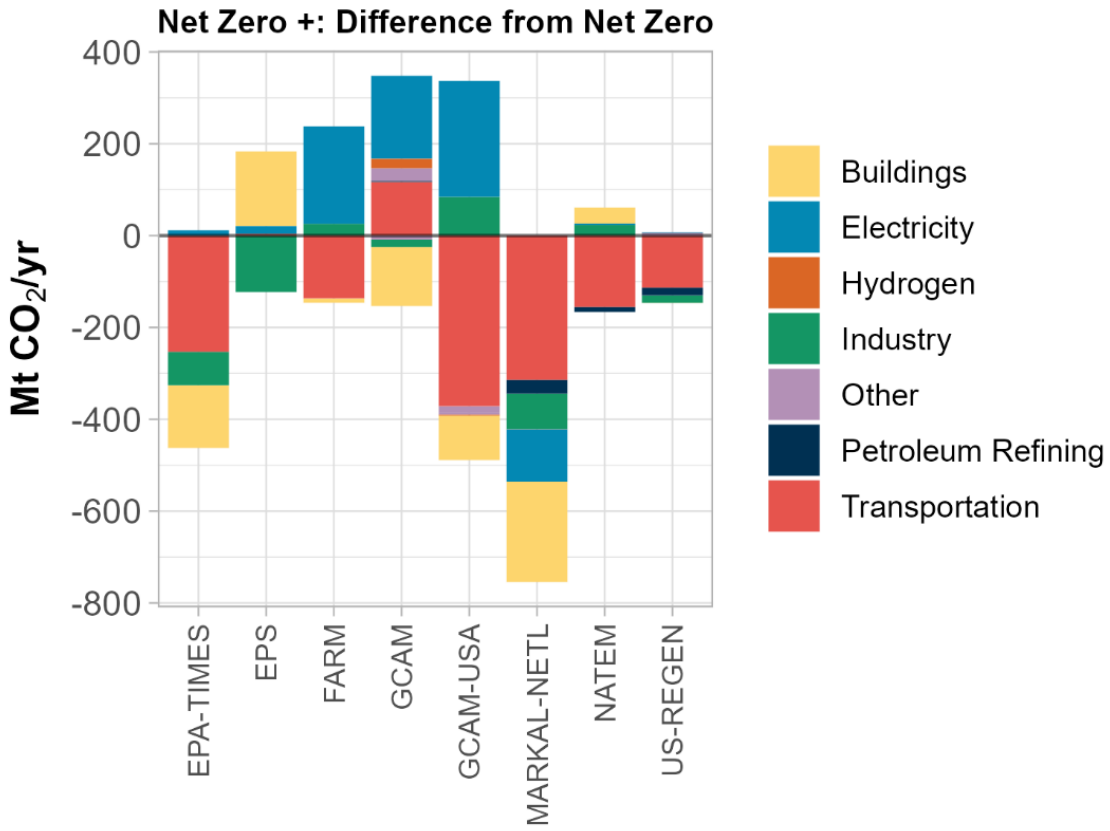

Figure 9. (Figure SM1.4 in the supplementary material for Browning, et. Al., 2024) SM1.4. Difference in 2050 residual sectoral emissions by model between the Net Zero and Net Zero+ scenarios.

Energy

Although emissions projections are crucial climate policy outputs for the EMF 37 and EDITS studies the most useful comparative outputs are the underlying energy demand totals. As observed in both projects perhaps the most useful measure of energy demand would be the amount of energy end-use services demanded but, largely because of lack of publicly available data at that level means that this information is not typically outputted from energy systems models. Note that this does not mean that reductions in energy services are not explicitly considered in such models, but as the EDITS community has stressed this often leads to less

consideration of energy demand reductions rather than energy supply technology decreases in energy demand and GHG emissions. In EMF 37 an attempt was made to consider changes in end-use technologies, changes in behavior by industrial and household energy consumers, changes in regulations impacting final energy demand decisions and changes in end use service demands, these adjustment pathways generally become more difficult to incorporate into the models in this order.

Although energy service demand levels were not generally reported for the EMF 37 scenarios, final energy demand by consuming sector are generally reported and a look at those results can give us some idea of how well demand side reductions in energy demands and emissions were considered. This information can thus, be at least partially be compared to kinds of new scenarios the EDITS network is encouraging. Although not a perfect metric for diagnostic purposes the trends in EMF 37 final energy demand projections provide some basis for comparison with the EDITS High-with-Low scenario specification.

The targets for the HwL scenario are presented in Wilson, et al. (2023) and shown here in Figure 9 which 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 10 (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).

The overall development pattern of the HwL scenario is therefore one of conditional convergence in which energy services for well-being increase substantially in the Global South catching up to levels maintained in the Global North, while associated resource use tends to converge, combining a contraction in the Global North with relatively modest increases in the Global South.

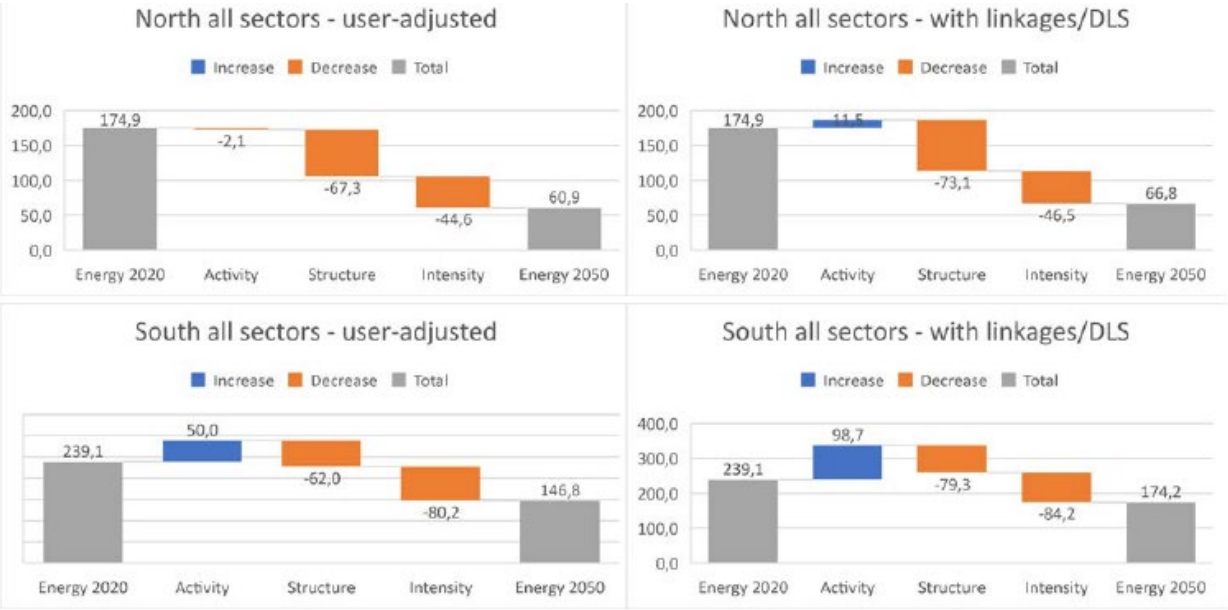

Figure 10. Changes in final energy use from 2020 to 2050 decomposed into activity, structure, and intensity components in a High-with-Low scenario, distinguishing: (1) Global North (upper panels) and Global South (lower panels); (2) user-adjusted global LED scenario (left panels) and inter-sectoral linkages and DLS scenario (right panels). All units in EJ/yr.

Final energy demand projections for the three core EMF 37 scenarios are shown in Figures 11 and 12. At the highest level we see that changes in EMF 37 final energy demand between 2020 and 2050 range between about minus 30% to plus 25% in the Net Zero scenario and between

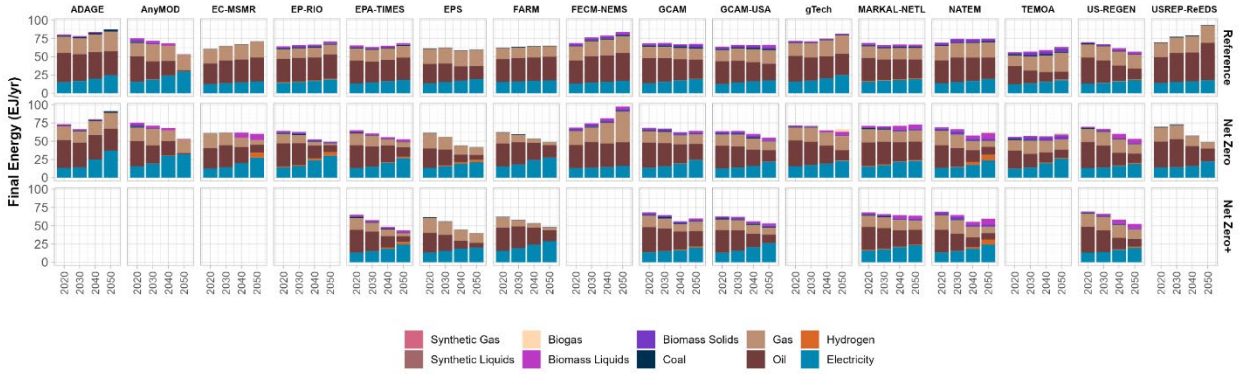

Figure 11 (Figure SM1.9 from the supplementary material for Browning, et al, 2024). Final Energy by model over time. This figure shows the final energy use by fuel type for all end-use sectors.

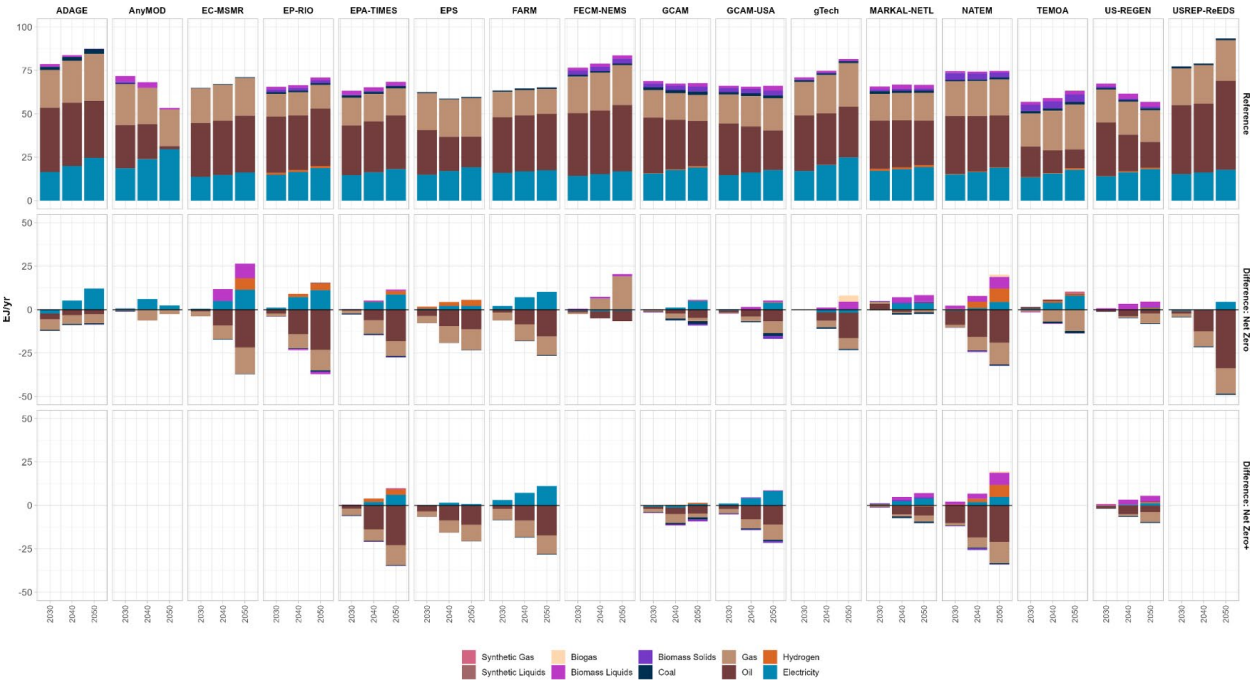

Figure 12 (Figure 5 from Browning, et al, 2024). Final Energy by Fuel Over Time. This figure shows absolute final energy by fuel for the Reference scenario in the top panel. The bottom two panels show the difference between the Net Zero and Net Zero+ scenarios and the Reference scenario. Note: The value range differs from the Reference and Net Zero scenario panels, but the magnitude is equal.

about minus 35% and minus 5% in the Net Zero+ scenario. By contrast the reductions in final energy demands in the global north called for in the EDITS HwL scenario ranges for minus 65% in the user adjusted case and minus 62% in the with linkages/DLS scenario.

The EMF 37 results are driven by standard GDP projections as shown here in Figure 13.

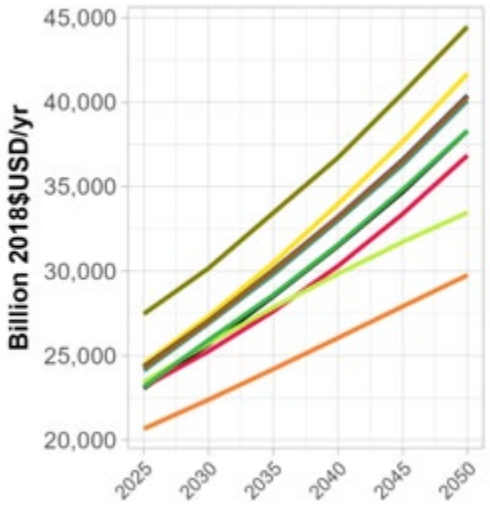

Figure 13 (Figure SM1.1 from the supplementary material for Browning, et al, 2024). GDP by model over time for the Reference Scenario.

One rough decomposition of results that can help understand these differences is to net out the differences in economic activity levels assumed in the two studies. In the EDITS HwL scenario the change in economic activity between 2020 and 2050 are minus 1.2 % in the user adjusted case and plus 6.5 % in the with linkages/DLS case whereas the change on the EMF 37 reference case GDP (activity) projections range between about plus 50% and plus 60%. This is a major difference and if the 2050 EDITS 2050 requirements are scaled up linearly by 60%, we would then get a final energy demand change projection of about 39% which is very close to the range of EMF 37 projections for the Net Zero+ scenario. This observation has three implications.

First it is clear that the EMF 37 projections do not go nearly as far as EDITS suggests in the direction of alternatives to the standard GDP economic activity metrics, (2) the demand side technology and technology choice and rate of introduction called for in EDITS and EMF 37 are

roughly similar, and (3) related to observation (1), additional effort should go into understanding the differences between the standard GDP activity metric and the EDITS welfare/equity metrics.

Figures 13-15 dis-aggregate the EMF 37 final energy demand results by consuming sector to give further insight into where the reductions in final energy demand are projected to occur. These results show less potential for demand reductions than the buildings and transport sector although all three of these trends could usefully be decomposed farther as is happening in some of the individual modeling team and cross cut papers being produced to document the results of the study with differences between the different models driving a lot of the inquiry,

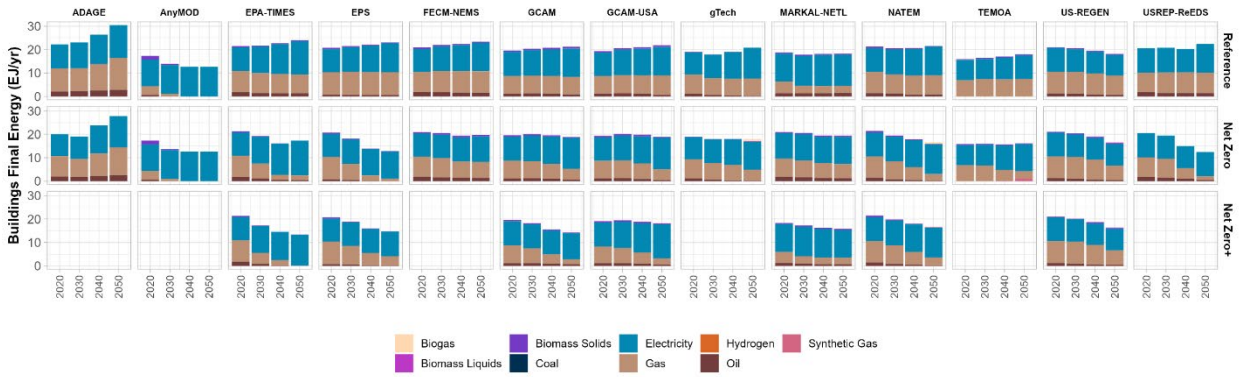

Figure 14 (Figure SM1.10 from the supplementary material for Browning, et al, 2024)**.** Buildings final energy by fuel over time.

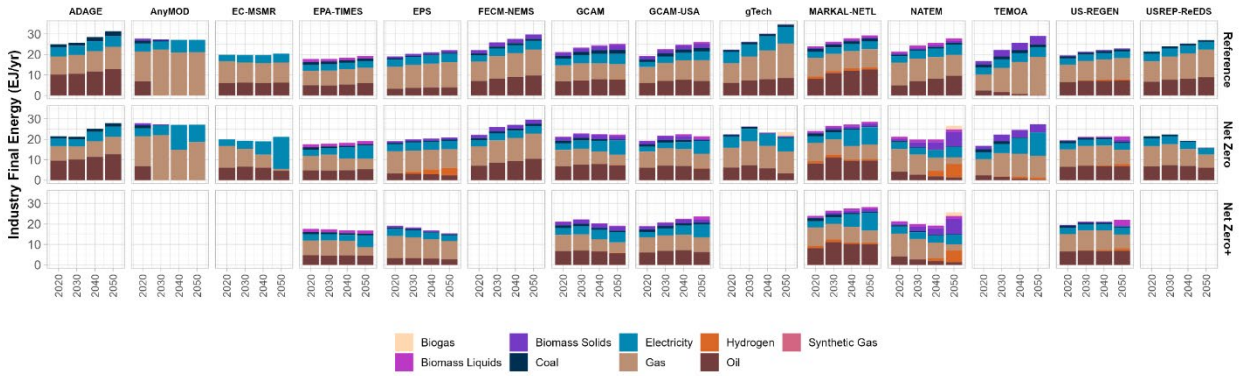

Figure 15 (Figure SM1.11 from the supplementary material for Browning, et al, 2024). SM1.11. Industry final energy by fuel over time.

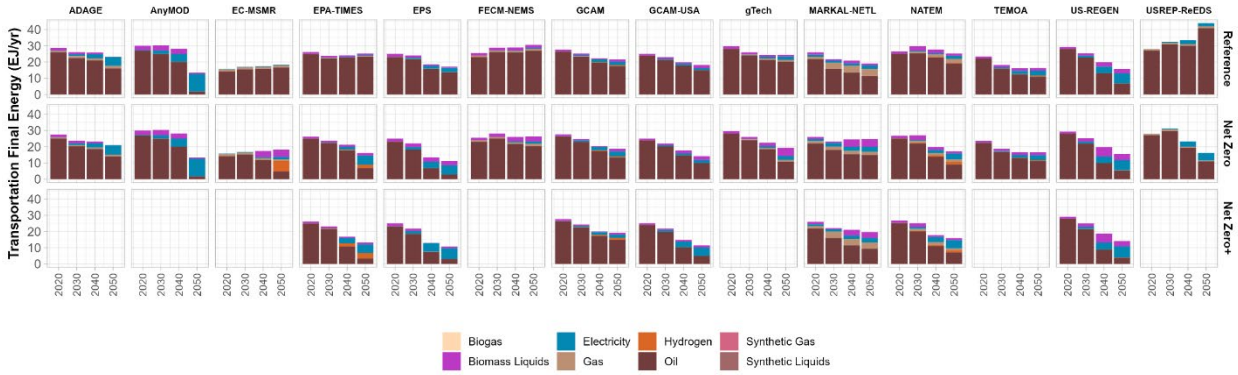

Figure 16 (Figure SM1.12 from the supplementary material for Browning, et al, 2024).Transportation final energy by fuel over time.

An EDITS community recommendation that this analysis strongly supports is the request to the research community and research assessment community to produce more scenarios with more comprehensive energy demand side specifications and encourage more reporting of more granular results that would support interpretation and cross comparisons of those scenarios. The relevant paper and variable reporting observed in the IPCC's sixth assessment report are shown in Figure 17.

As shown above, the results from the EMF 37 project, as well of course as contributions by the EDITS network will partially remedy this situation, but much more needs to be done and the urgency with which this information is required over the next five to ten years is extreme and critical.

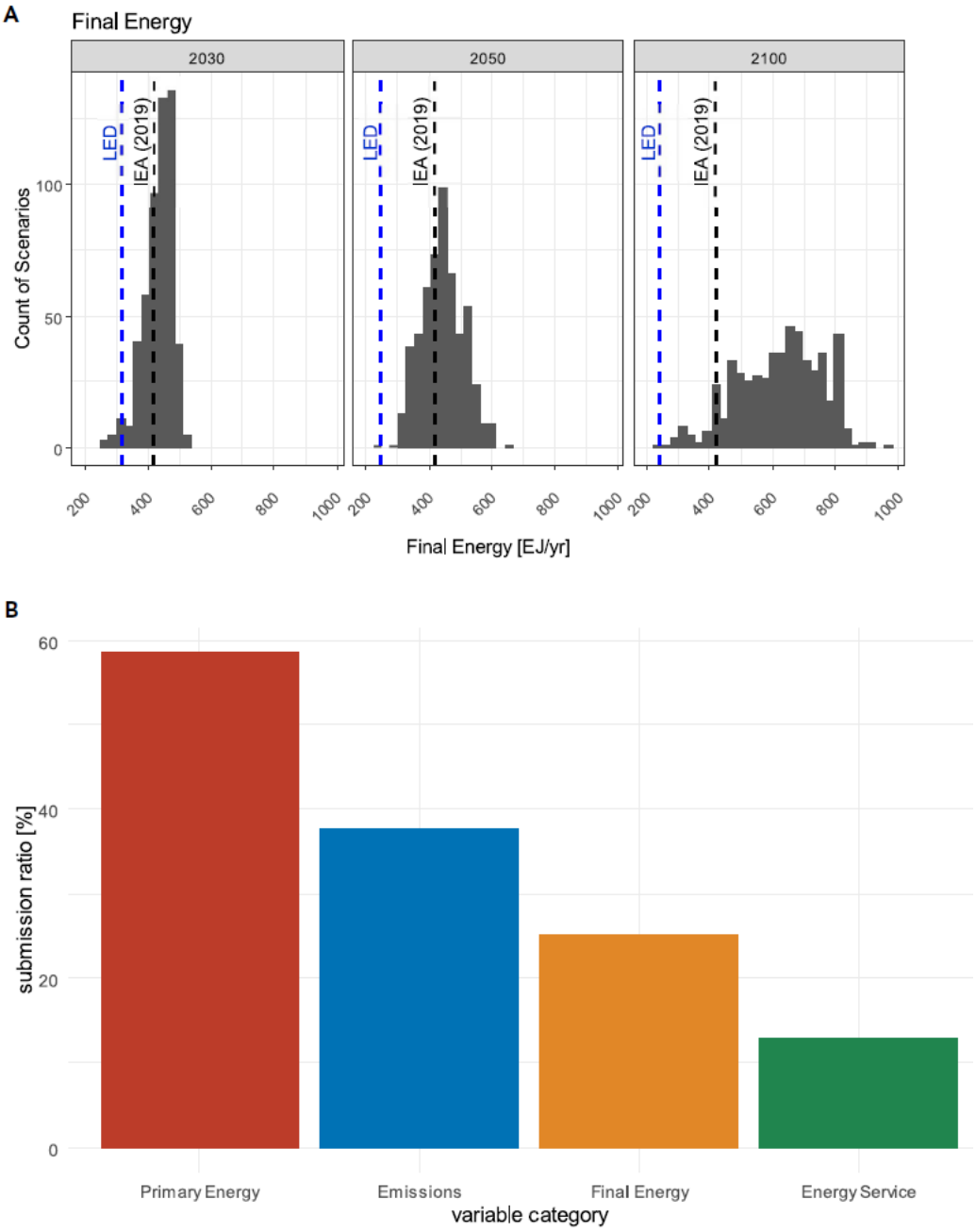

Figure 17 (Figure 2 from Sugiyama, et al.). The IPCC scenario database contains only a small number of LEMD scenarios, and it
does not provide sufficient granularity for demand-side analysis
(A) Distribution of final energy consumption in the IPCC AR6 scenario database for 2030, 2050, and 2100. The blue dashed vertical line indicates the original LED scenario,6 which was also presented as an illustrative mitigation pathway in the IPCC, and the black dashed vertical line represents the total final energy consumption in 2019 from the International Energy Agency statistics. See Figures S1–S3 for sectoral breakdowns.
(B) Submission rate of variables to the IPCC AR6 Scenario Explorer, defined as the number of the variables submitted, divided by the number of unique models times the number of unique variables. For both (A) and (B), only the scenarios consistent with the Paris Agreement (peak warming of 2_C or less with >67% probability; scenario categories C1, C2, and C3) are used.

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 review.

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 development, including by reducing inequality, can lead to mitigation (IMP-SP). The IMPs reach different climate goals as indicated in Figure 18 (IPCC, 2022).

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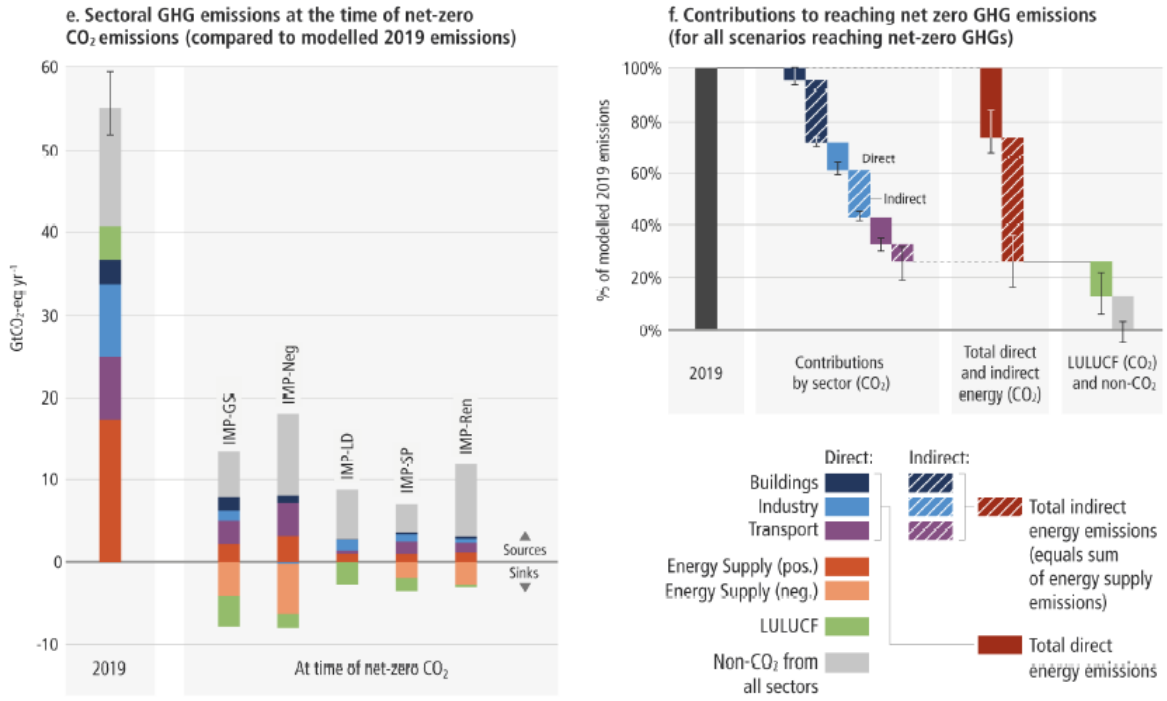

Figure 18. Illustrative Mitigation Emissions Pathways (IMPs) and net zero CO2 and GHG emissions strategies (Figure SPM 5 from IPCC, 2022)

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 range[7]. 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.

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.,

[7] Note these are 5th and 95th percentiles of the reported scenario results and not proabbilitiy distributions.

IMP-LD) or shift global development towards sustainability (e.g., IMP-SP) as illustrated in Figure 18 here which is figure SPM-5 in the AR6 Summary for Policy Makers from Working Group 3 (IPCC, 2022) is shown here.

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. 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. In fact, preliminary results from EMF 37 indicate that although it has created more demand side emphasis and detail in energy systems model projections for the US and has probably included as much detail as in the EDITS HwL scenario in the end use technology economics, technology choice, regulatory and behavior dimensions it did not include nearly as much detail and results in the low energy service demand and alternative materials dimensions as called for by the EDITS community. This is related both to a lack of appropriate options and detail in these areas in EMF 37 and the direct use of a set

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community welfare point metrics in designing the activity levels to be achieved in EDITS HwL scenario rather than the relying on GDP and population driven activities that direct the EMF 37 scenarios.

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.

v. **It is clear that (1) the EMF 37 projections do not go nearly as far as EDITS suggests in the direction of alternatives to the standard GDP economic activity metrics, (2) the demand side technology and technology choice and rate of introduction called for in EDITS and EMF 37 are roughly similar, and (3) related to observation (1).**
Additional effort should go into understanding the differences between the EMF 37 standard GDP activity metrics and the EDITS welfare/equity metrics (DLS). One idea would be to require a comparison of integrated EDITS results with those based on standard activity metrics which should be possible given that the current EDIT results are integrated using energy systems or full integrated assessment models.

vi. **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.

vii. **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**

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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.

viii. **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 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 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 plans for running some coordinated scenarios across the two studies.

Appendix A

Scenarios for Deep Decarbonization of Manufacturing[8] (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

[8] 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[9] 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[10] 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

[9] It should be noted that within this sector there are some larger energy users; food processing and metal based durables being the most obvious.

[10] 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

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.

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:

ix. **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.

x. **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

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

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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.

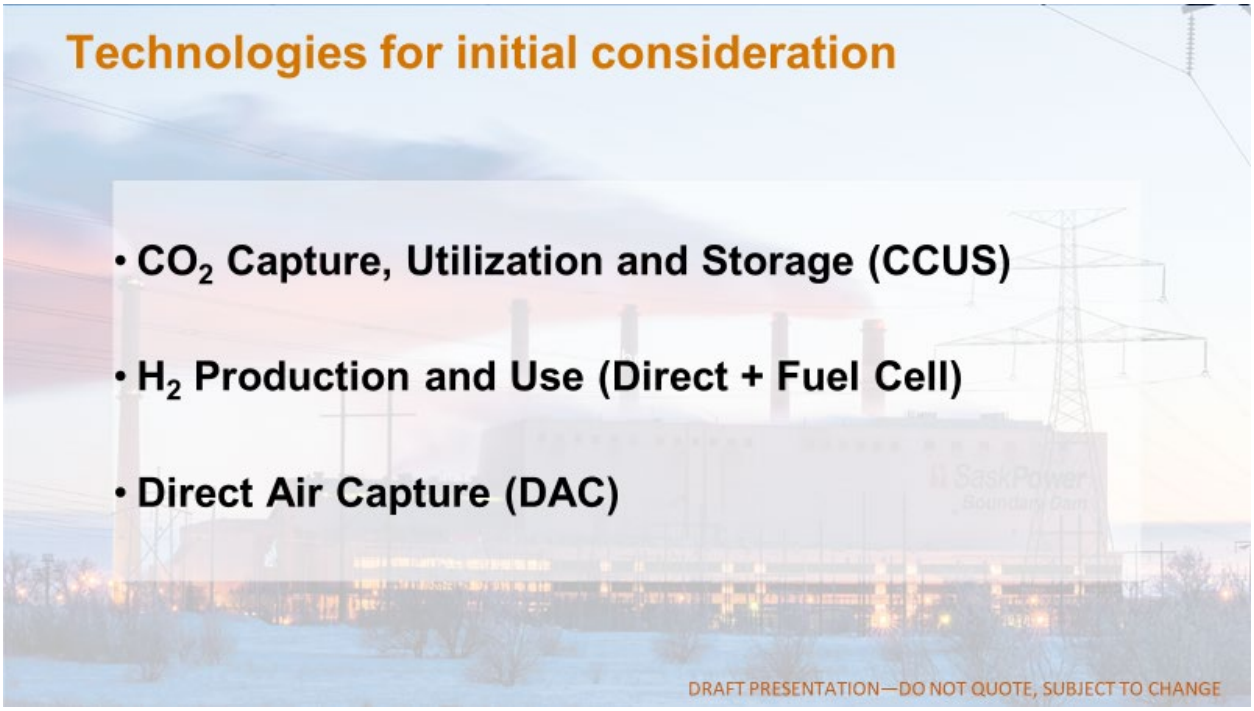
Scenario 8: Narrative for Model Implementation

- **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

Core Scenarios				
Policy Goal Technology Set	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		

CMSG Scenarios

EMF37 Core and Carbon Management Study Group (CMSG) Scenarios

Scenario ↓	Technology: CCS	Technology: H2 production and use	Technology: DAC	BAU	Net Zero Year: 2050	Net Zero Year: 2060	Net Zero Year: 2080	Priority Order
EMF37 Reference	Ref	Ref	Ref	EMF37-01	EMF37-02	EMF37-03	EMF37-04	Priority 1
CMSG-1	None	Ref	None		CMSG-01-2050	CMSG-01-2060	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

Scenario ↓	Technology: CCS	Technology: H2 production and use	Technology: 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-01-2080	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
						2060	CMSG-04-2080	
						5-2060	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-01-2060	CMSG-01-2080	Priority 2
CMSG-2	Adv	Ref	Ref		CMSG-02-2050	CMSG-		Priority 3
CMSG-3	Ref	Adv	Ref		CMSG-03-2050		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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Source https://grist.org/energy/europe-is-going-all-in-on-hydrogen-why-not-the-us/

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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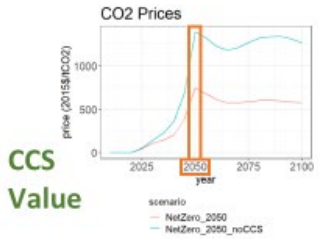
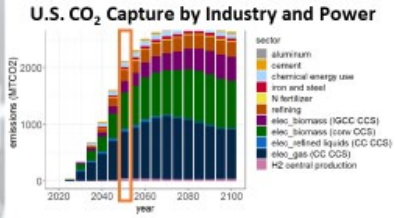
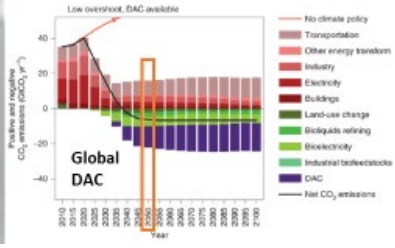
CCS Value







Appendix E
Table E-1
EMF 37 Paper Pipeline

⓫ Stanford Univ.

Appendix F

Table F-1

EMF 37 Model attributes, website, and publications

Model Name (Institution)	Other unique and important attributes	Model Website	Peer-reviewed Publication
ADAGE* (RTI International)	World faces one price for crude oil but different price for other energy in import and export	https://github.com/ICTatRTI/ADAGE	
AnyMOD^ (TU Berlin)		https://leonardgoeke.github.io/AnyMOD.jl/stable/	https://doi.org/10.1016/j.softx.2021.100871; https://doi.org/10.1016/j.apenergy.2021.117377
EC-MSMR* (Environment and Climate Change Canada)	Oil extraction in Canada is disaggregated into 8 extraction technologies (Conventional and unconventional)	Model assumptions can be found in the Annex from Canada's Long Term Strategy submission to UNFCCC (pg.55) https://unfccc.int/sites/default/files/resource/LTS%20Full%20Draft_Final%20version_oct31.pdf	Key findings from the core North American scenarios in the EMF34 intermodel comparison. Huntington, H. G., Bhargava, A., Daniels, D., Weyant, J. P., Avraam, C., Bistline, J., ... & Johnston, P. (2020). Energy Policy, 144, 111599
EnergyPATHWAYS and RIO [EP-RIO.2022.1] (Evolved Energy)	16 final energy types passed from EP to RIO; hourly demand shapes produced bottom-up for electricity, pipeline gas, hydrogen, and steam; new electricity transmission and 3 pipeline types are included in the optimization (h2, CO2, and ammonia); salt cavern h2 storage allowed in some zones based on geology, other zones use tank storage; distribution expansion is approximated using three feeder 'archetypes' per zone (residential, commercial, industrial) w transportation load allocated to one of the three feeders, flexible load and BTM PV are located on feeders and can avoid distribution peaks; state of charge linkages for electric and fuel storage between sample days allow for long duration storage; energy blends can be made carbon neutral with drop-in fuels (bio or synthetic) allowing for existing thermal generators to become carbon neutral by changing the fuel upstream; industrial steam production is included in the optimization; advanced nuclear and steam production have the option to build thermal storage.	www.evolved.energy	https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000284
EPA-TIMES* (USEPA/ORD)	Contains a detailed representation of air pollutant and non-CO2 greenhouse gas emissions across the energy system.	https://www.epa.gov/air-research/epaus9rt-energy-systems-database-use-times-model	
EPS* (Energy Innovation)	embedded downstream I-O model with feedbacks on a one-year delay	https://energypolicy.solutions	
FARM* (USDA)	Food crops, energy crops, forest products, and livestock compete for land within six agro-ecological zones (AEZs); base-year food demand and crop production calibrated to FAO Food Balance Sheets	Model documentation in Economic Research Report 223 https://www.ers.usda.gov/publications/pub-details/?pubid=81902	U.S. Carbon Tax Scenarios and Bioenergy, https://doi.org/10.1142/S2010007818400109

FECM-NEMS^ & OP-NEMS (OnLocation)	The CO2 transport utilization and storage (CTUS) module builds an optimal pipeline network linking CO2 sources to explicit EOR and saline storage sites to determine regional CO2 transport and storage costs. Added features to the AEO2022 version include industrial CCS in several industries, BECCS retrofits, and DAC.	Modified version of National Energy Modeling System (NEMS) based on 2022 Annual Energy Outlook. https://www.onlocationinc.com/national-energy-modeling-system-nems	EIA 2022 Annual Energy Outlook. https://www.eia.gov/outlooks/aeo/
GCAM and GCAM-USA• (PNNL/University of Maryland)	full land system including agricultural production (food crops, bioenergy crops), endogenous terrestrial emissions; traditional air pollutants in addition to GHGs; fully hydrology representation	https://github.com/JGCRI/gcam-core; http://jgcri.github.io/gcam-doc/toc.html	1. Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Cui, R. Y., Di Vittorio, A., Dorheim, K., Edmonds, J., Hartin, C., Hejazi, M., Horowitz, R., Iyer, G., Kyle, P., Kim, S., Link, R., McJeon, H., Smith, S. J., Snyder, A., Waldhoff, S., and Wise, M.: GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems, Geosci. Model Dev., 12, 677–698, https://doi.org/10.5194/gmd-12-677-2019, 2019. 2. Hultman N., L.E. Clarke, C. Frisch, K. Kennedy, H.C. McJeon, T. Cyrs, and P. Hansel, et al. 2020. "Fusing subnational with national climate action is central to decarbonization: the case of the United States." Nature Communications 11, no. 1: 5255.
gTech• (Navius Research)		https://www.naviusresearch.com/gtech/	
MA3T•• (ORNL)	Implemented using Microsoft Excel for Windows, the Market Acceptance of Advanced Automotive Technologies (MA3T) model simulates market demand for advanced vehicle technologies by representing relevant attributes of technologies and consumer behavior such as technological learning by doing, range anxiety, access to recharging points, daily driving patterns, and willingness to accept technological innovation. MA3T projections currently cover the period from 2005 to 2050 and capture the temporal interaction between market penetrations and product diversity and risk for light-duty, mid-duty, and heavy-duty vehicles in the 50 states of the U.S. The analysis of MA3T has been extended to the used vehicle market, the shared/autonomous market, and the global market as well	https://teem.ornl.gov/ma3t.shtml	1. Ou, S., Lin, Z., Jiang, Y., & Zhang, S. (2022). Quantifying policy gaps for achieving the net-zero GHG emissions target in the US light-duty vehicle market through electrification. Journal of Cleaner Production, 380, 135000. 2. Ou, S., Gohlke, D., & Lin, Z. (2020). Quantifying the impacts of micro-and mild-hybrid vehicle technologies on fleetwide fuel economy and electrification. ETransportation, 4, 100058. 3. Dong, J., & Lin, Z. (2012). Exploring the Paths to One

			Million Plug-in Electric Vehicles by 2015 Using MA3T Model. World Electric Vehicle Journal, 5(4), 953-959.
MARKAL-NETL (NETL)	MARKAL subdivides the year into three seasons Z (summer, winter, intermediate) and 4 times of day Y (day am, day pm, night, and peak). In addition to 9 CENSUS regions, there is a "dummy" supply region R0, for coal and imported fuels. For each of the 9 regions, there an export option in R0 linked to an associated import option in the region for each commodity.	https://iea-etsap.org/index.php/etsaptool/model-generators/markal	Victor, N., Nichols, C. (2022), CCUS Deployment under the U.S. 45Q Tax Credit and Adaptation by Other North American Governments: MARKAL Modeling Results, Computers & Industrial Engineering, Volume 169, July 2022, 108269
NATEM* (Esmia Consultants)	Four seasons (summer, winter, spring, fall) and 4 times of day (day am, day pm, night, and peak). Technological hurdle rates, demand price elasticities.	www.esmia.ca	
ReEDS** (NREL)	Detailed spatial and temporal representation for wind and solar	https://www.nrel.gov/analysis/reeds/	
Scout** (DOE; NREL and LBNL)	Sub-annual impacts of efficiency and fuel switching are captured using hourly load profiles and savings shapes derived from EnergyPlus models of residential and commercial buildings. Model baseline/BAU scenario is exogenous, derived (almost) entirely from NEMS-AEO.	scout.energy.gov; github.com/trynthink/scout	https://doi.org/10.1016/j.joule.2021.06.002 https://doi.org/10.1016/j.joule.2019.07.013
TEMOA* (North Carolina State University)	TEMOA subdivides the year into three seasons (summer, winter, intermediate) and 4 times of day (day am, day pm, night, and peak). Other formulations also include representative day treatments with up to 8 representative days currently. A key feature of the model formulation is that end-use technology selection is endogenous, driven by end-use service demands.	https://temoacloud.com/ ; https://www.cmu.edu/energy/key-initiatives/open-energy-outlook/index.html	Hunter, Kevin, Sarat Sreepathi, and Joseph F. DeCarolis. "Modeling for insight using tools for energy model optimization and analysis (Temoa)." Energy Economics 40 (2013): 339-349.
TEMPO** (NREL)	The Transportation Energy & Mobility Pathway Options™ (TEMPO) model is an all-inclusive transportation demand model that covers the entire United States. Researchers use the TEMPO model to explore pathway options for producing long-term scenarios that reach strategic transportation-energy-environment objectives and to assess synergies with energy supply. TEMPO characterizes opportunities for existing and future fuels, technologies, and business models across all passenger and freight transportation sub-sectors and segments.	https://www.nrel.gov/transportation/tempo-model.html	

US-REGEN** (EPRI)	Detailed temporal, spatial, and technological resolution to capture system operations and investments; Integrated modeling framework representing energy supply, conversion, storage, and demand; Broad coverage of existing and emerging technologies informed by EPRI technological cost and performance assessments; Energy demand model includes differences across households and businesses to account for both behavioral and financial drivers of technology adoption.	https://us-regen-docs.epri.com/v2021a/	https://www.nature.com/articles/s41467-022-33902-9 https://www.nature.com/articles/s41467-021-23554-6 https://www.nature.com/articles/s41467-022-32468-w
USREP-ReEDS** (MIT-NREL)		USREP (https://globalchange.mit.edu/sites/default/files/MITJPSPGC_TechNote18.pdf); ReEDS (https://www.nrel.gov/docs/fy21osti/78195.pdf)	https://iopscience.iop.org/article/10.1088/1748-9326/ac6227

** Single sector models participating in EMF 37, but are not included in this paper.

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

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Summary

In FY2022, we launched the model complementarity exercise (MCE) protocol, prepared the input variable list, output variable template and made a call for submission across EDITS community. To further facilitate MCE, in FY2023, we established the platform, just like IPCC AR6 Scenario Explorer, for the sake of data submission and comparison, and made an instruction for manipulating the Explorer. Till the end of FY2023, we have received scenario data from 13 models covering 4 scenarios (cross-aligned combination of climate goal and HwL narratives) and 3 sectors (Industry, residential and commercial, and transportation). Based on the existed data, we made some preliminary analysis based on Activity-Structure-Intensity framework and Kaya-like decomposition method. Lastly, we published one commentary paper in the journal *Joule*, calling for advancement in demand-side modeling. Next year, we plan to focus on a small set of research questions with modelers to extend the current Activity-Structure-Intensity framework.

Evidence synthesis of indirect impacts of digitalisation on energy and emissions

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Abstract
The indirect impacts of digitalisation on energy use and carbon emissions are large but uncertain. Digital applications can improve process efficiency, optimise system performance, and substitute for energy-intensive activities; but reducing cost and friction can also induce demand (rebound effect) and expand or intensify energy use. In 2017 the International Energy Agency (IEA) provided quantitative estimates of the indirect impacts of digitalisation on energy use in buildings, transport, industry, and upstream resource sectors, drawing on select use cases. Estimates in this landmark IEA assessment varied by sector but were typically in the order of 5-15%, with an emphasis on demand reduction.

In this study, we provide updated ranges of quantitative impacts of digitalisation on energy use by sector, focusing not just on reduction potentials but also observed increases due to rebound or induced demand.

We identify the digital applications with highest magnitude impact in each sector. We then synthesise recent literature providing quantitative estimates of impacts, focusing where possible on empirical rather than simulation modelling studies.

For transport, buildings, consumer goods, and industry sectors, we draw on studies of specific use cases and normalise impact estimates as % changes relative to reference cases without the digital application. We then present the maximum uncertainty ranges of impact estimates by application and explore the conditions explaining both lower and upper bounds of the range. For all our %Δ estimates we distinguish activity, energy, and emission metrics.

Our aim is to provide a first order synthesis of the indirect impacts of digitalisation on energy use in different sectors, identifying both opportunities and risks in order to inform scenario and modelling assessments of future pathways with high wellbeing but low resource demands.

For digital applications in transport, consumer goods, and buildings sectors we find strong evidence of both large reductions in energy use (e.g., shared ridehailing: -55% to -18%) and large increases in energy use (e.g., ridehailing: +41 to +90%). For many digital applications, we find evidence of both negative and positive impacts depending on context and user response (e.g., e-retail: -94% to +140%; smart heating: -36% to +2%). Impact estimates have larger ranges for applications for which deployment conditions can be very different (e.g., mobility-as-a-service, MaaS: -50% to +20%; usership: -100 to +100%). In the industry sector, evidence points only to reductions in energy use. This is due to study designs that exclude net energy-increasing effects.

Study design and system boundaries affect the uncertainty of digitalisation impacts. First, empirical studies based on observational data from real-world deployment tend to report narrower ranges than simulation studies. Second, studies reporting impact estimates using activity metrics tend to have wider ranges than those reporting energy or carbon metrics. However, the three metrics are generally consistent in direction and magnitude. Third, a major source of impact variation towards the upper bound is whether system boundaries

account for rebound or induced demand effects; such studies are the exception rather than the rule.

In interpreting impact ranges per application, we find clear evidence of digitalisation mechanisms that reduce energy use including substitution effects, optimisation, efficiency improvements, and waste avoidance. We also find clear evidence of digitalisation mechanisms that increase energy use including perverse substitution effects (e.g., shared mobility substituting for active modes), rebound effects (e.g., increased consumption of easy-to-access online goods), and induced demand or intensification effects (e.g., use of new services). Some applications show significant potential to undermine efforts to reduce emissions unless carefully managed (e.g., ride-hailing: %Δ up to +90%; e.g., autonomous vehicles, AVs: %Δ up to +60%; peer-to-peer platforms for goods: %Δ up to +55%; e-retail: %Δ up to +140%).

Overall, our evidence synthesis of the impacts of digitalisation in transport, buildings, consumer goods, and industry shows clear potentials to reduce energy demand, but with specific and identifiable risks of intensification and rebound in some cases. The conditions we identify that explain the lower and upper bounds of the impact ranges help informed deployment and policy to ensure digitalisation contributes to net-zero goals.

Although observed impacts of discrete applications can be large (both negative and positive), these are diluted when scaling from best or worse cases to aggregate effects across whole sectors. As a result, energy demand reduction potentials from digitalisation are not transformative in isolation but need to exploit synergies with other decarbonisation processes.

Keywords
digital applications, use cases, activity, carbon, climate

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Findings: Material stocks for Decent Living Standards around the world

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1) Deliverables for the fiscal year 2023/24

In 2023/24 the University of Natural Resources and Life Sciences Vienna (BOKU) led two main research contributions within EDITS, and contributed to several efforts from the EDITS consortium. As specified in the contract for the financial year 2023/24, we herein submit the deliverable including the following contents:

- Final version of the "review of industry modelling for low energy and material demand scenarios", which has been submitted to the peer-reviewed journal *Annual Review of Environment and Resources* (*ARER*) in 09/2024, and which is currently under revision (section 2). The pre-print is freely available, has been shared with IIASA and within EDITS, and can be published on METIs website.
- Second, findings on "Material Stocks for Decent Living Standards around the world", which are in an advanced stage and manuscript preparation is currently ongoing. Submission to a peer-reviewed journal is foreseen in Spring 2024. Herein, we include an extended summary of preliminary findings which can be shared on METIs website (section 3).
- Furthermore, BOKU facilitated and participated in the annual meetings, the quarterly meetings, working group meetings, as well as specific research meetings for active collaborations between working groups and contributions to ongoing research efforts across EDITS.

In 2023/24, additional contributions to EDITS include the following publications, which have been shared with IIASA and the EDITS consortium and which have been reported to IIASA:

Mastrucci, Alessio, Leila Niamir, Benigna Boza-Kiss, Nuno Bento, **Dominik Wiedenhofer, Jan Streeck,** Shonali Pachauri, et al. „Modeling Low Energy Demand Futures for Buildings: Current State and Research Needs". *Annual Review of Environment and Resources* 48, Nr. 1 (2023): 761–92. https://doi.org/10.1146/annurev-environ-112321-102921.

Sugiyama, Masahiro, Charlie Wilson, **Dominik Wiedenhofer,** Benigna Boza-Kiss, Tao Cao, Joyee S. Chatterjee, Souran Chatterjee, et al. „High with low: Harnessing the power of demand-side solutions for high wellbeing with low energy and material demand". *Joule* 8, Nr 1 (2024): 1–6. https://doi.org/10.1016/j.joule.2023.12.014.

Wiedenhofer, Dominik, André Baumgart, Sarah Matej, Doris Virág, Gerald Kalt, Maud Lanau, Danielle Densley Tingley, et al. „Mapping and modelling global mobility infrastructure stocks, material flows and their embodied greenhouse gas emissions". *Journal of Cleaner Production* 434 (2024): 139742. https://doi.org/10.1016/j.jclepro.2023.139742.

2) Summary of the Review: *Material Cycles, Industry and Service Provisioning: A Review of Low Energy and Material Demand Modelling and Scenarios*

In the article, we review recent innovative literature on Low Energy and Material Demand (LEMD) scenario models within the context of sustainable industry practices, service provisioning and climate change mitigation. Specifically, we focus on transformative pathways to align industry's material cycles and global supply chains with international climate targets, emphasizing the importance of demand-side measures in comparison to technology-oriented supply-side measures. The review identifies 77 innovative studies across nine modelling traditions, discussing their approaches, system definitions, and operationalization of demand and service provision.

We find that while the reviewed studies show large reduction potentials of reducing material use, energy consumption, and greenhouse gas emissions through combined supply- and demand-side measures, modelling is often inconsistent and poorly documented. Over all studies, we find the maximum potentials to reduce current economy-wide material use by -56%, energy use by -40 to -60%, and GHG emissions by -70% to net-zero. However, the materials-energy-GHG nexus is usually not represented with thermodynamic consistency, except in those traditions focused on the biophysical basis of society.

Concluding, we call for improved system linkages and consistency, increased interdisciplinary collaborations, as well as more rigorous documentation and open data practices to enhance robustness, comparability and synthesis of model outputs to advance LEMD scenario modelling. System linkages and consistency require improved modelling of environmental flows and service units in stock-flow consistent physical units and at higher granularity, as well as representing system feedbacks, non-linearities and telecoupling. These properties are usually better represented in interdisciplinary model outcomes, leading to more robust results. Last but not least, proper documentation is a crucial enabler for evidence synthesis with harmonized system boundaries, which with the current reporting of results was hardly possible. Documentation and transparency could also be further enhanced via stronger connection to ongoing efforts to improve the Shared Socio-economic Pathways (SSPs) framework.

The article is currently available as preprint, which you can also find in the Annex. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4617908

3) Preliminary findings on: *Material stocks and flows for closing global gaps in Decent Living Standards*

Introduction

Despite surging resource use and related environmental impacts (UNEP-IRP 2019; UN Environment 2019), large parts of the global population live in poverty (UN DESA 2022). The majority of growing resource use caters towards the affluent lifestyles of the world's wealthy (Teixidó-Figueras et al. 2016; Wiedmann et al. 2020). In comparison, resource use of the poorest is low and enabling 'just access' levels of consumption would require only small increases in environmental impacts (Rammelt et al. 2022).

To measure universal living standards required to eradicate poverty, Rao and Min (2018) propose the concept of Decent Living Standards centered around biophysical services (e.g., kcal nutrition, m² housing, person-kilometer mobility), instead of monetary income (SDG 1). Decent Living Standards (DLS) define a universal set of material satisfiers (e.g., nutrition, shelter, mobility) with quantitative thresholds above which service levels are deemed 'decent'. DLS can thus be interpreted as a minimum universal threshold. While these thresholds in reality are also context-dependent (Rao and Min 2018), they enable a first estimate of the resource requirements for a decent life, vis à vis overall resource use.

To reach DLS globally, recent research found the required DLS final energy use (DLE) and GHG emissions to only be a fraction of overall annual use and emissions (Rao et al. 2019; Millward-Hopkins et al. 2020; Kikstra et al. 2021; Huo et al. 2023). For energy use, Rao et al. (2019) estimate annual prospective DLE per person in India, Brazil and South Africa 2050 to be 20-70% of national projections via IAMs; Millward-Hopkins et al. (2020) estimate global DLE in 2050 to be 60% lower than current energy use, and Kikstra et al. (2021) estimate global DLE in 2050 to be only 23-28% of SSP2 baseline projections. For GHGs, Huo et al. (2023) calculate a counterfactual scenario with constant 2019-emission-intensities, in which reaching DLS in emerging economies could cause 14.7 Gigatons CO_2, constituting 44% of global emissions in 2019 (IEA 2020).

Besides energy, the provision of services for DLS requires material flows (e.g., annual concrete- and steel use), as well as materials accumulated in durable goods and structures (= material stocks), such as buildings, infrastructure and machinery (Haberl et al. 2017; Thacker et al. 2019). In a pioneering study, Vélez-Henao and Pauliuk (2023) estimate threshold material

footprints and material stocks to reach global DLS at 3-14 tons/(capita*year) and 43 tons/capita respectively. Other work investigated the relationship of selective material stocks to various wellbeing indicators (Haberl et al. 2019; Fisch-Romito 2021; Virág et al. 2022), as well as embodied DLE (cited DLE studies) and embodied CO_2 in road access (Wenz et al. 2020); but no further work on DLS-materials is available.

This study addresses lacking estimates for DLS material stock gaps, regionalized thresholds at country-level, as well as comparison to current overall material stocks. We investigate the amount and composition of global material stocks that fulfill current DLS-levels versus the requirement to fill current gaps for 175 countries. Additionally, we contrast DLS- with current economy-wide material stocks, to estimate the amounts of materials which provide beyond-DLS services. We draw on updated DLS indicators by Kikstra et al. (2021) for the year ~2015, updated DLS-material intensities by Vélez-Henao and Pauliuk (2023), and total material stock estimates for economy-wide system boundaries (Wiedenhofer et al. (in prep.)), as well buildings and mobility infrastructure (Haberl et al. (in prep.)), Wiedenhofer et al. (2023)) to answer the following research questions (RQs):

1. *How much material stocks are currently used for DLS?*
2. *How much material stocks would need to be built to reach DLS for all?*
3. *Which share of countries' material stocks provides DLS versus beyond-DLS services?*
4. *What can be said about the resource-efficiency of providing DLS?*
5. *What do we know about the material (stock) requirements for DLS? What is missing? What are the uncertainties contained in estimates of DLS resource use?*

Methods

We investigate the material stocks that provide DLS & beyond-DLS services from three angles:

a) bottom-up – the material stocks that provide current levels of DLS and the gap to reach DLS for all via combining refined indicators on DLS thresholds and gaps from Kikstra et al. (2021) with refined material intensities from Vélez-Henao and Pauliuk (2023),

b) top-down –total material stocks accumulated when reaching DLS in a country cross-section via monovarietal regressions of per capita material stocks on 'DLS reached' expressed as relative fulfillment (0-100%) (the total stocks provide a combination of DLS and beyond-DLS services, and

c) combination of bottom-up/top-down – c1) material stocks that provide only beyond-DLS services via subtracting current DLS material stocks (bottom-up) from total, economy-wide stocks (top-down; (Wiedenhofer et al. in prep.)), and c2) beyond-DLS material stocks that would be built to close DLS gaps according to the current ratio of DLS- versus beyond-DLS stocks.

Preliminary findings

Current DLS material stocks & gaps around the globe

The achievement of DLS material stocks differs substantially around the globe (Figure 2a). While large parts of North America and Western Europe, as well as Australia, Japan and New Zealand fulfill >94% of material stocks required for DLS, less than 50% are reached in many Latin American, South and Pacific Asian and Sub-Saharan African countries. In Sub-Saharan Africa, 25 countries show fulfillments of <40%. The DLS material stock gap is largest in Sub-Saharan Africa with an average of 23 t/cap, followed by South Asia with 17 t/cap and compared to gaps of only ~1-3 t/cap in Europe, North America and PAO (Australia, Japan, New Zealand). For individual countries, material stock gaps range up to 30 t/cap in the Central African Republic (Figure 2c-d).

This inequality is despite the fact that regions of the global North require higher DLS material stocks to reach DLS thresholds than the global South, with average 58 tons per capita (t/cap) in Europe and 33 t/cap in Sub-Saharan Africa (Figure 2c). Across the 175 countries, the thresholds range between 32-70 t/cap. The reasons for diverging stock thresholds are on the one hand diverging DLS indicator thresholds (Kikstra et al., 2021) and on the other hand regional differences in diets, building material intensities and transport modal shares, which we adopted from current practices in 2015. Whether these thresholds are fair is up for discussion and might require adjustments to fair diets in nutrition (the current dietary composition might not depict decent nutrition beyond calories) and fair modal shares in mobility (the current modal shares might not depict decent mobility).

Regarding the currently available DLS stock by DLS dimensions, the largest material stocks are ubiquitously shelter, followed by mobility and nutrition, the order depending on the specific region (Figure 2a). An exception is Centrally Planned Asia (CPA), with extremely high current DLS stocks in nutrition, which can be explained by high consumption of pork which according to LCA database ecoinvent exhibits over proportionally high material stock intensities.

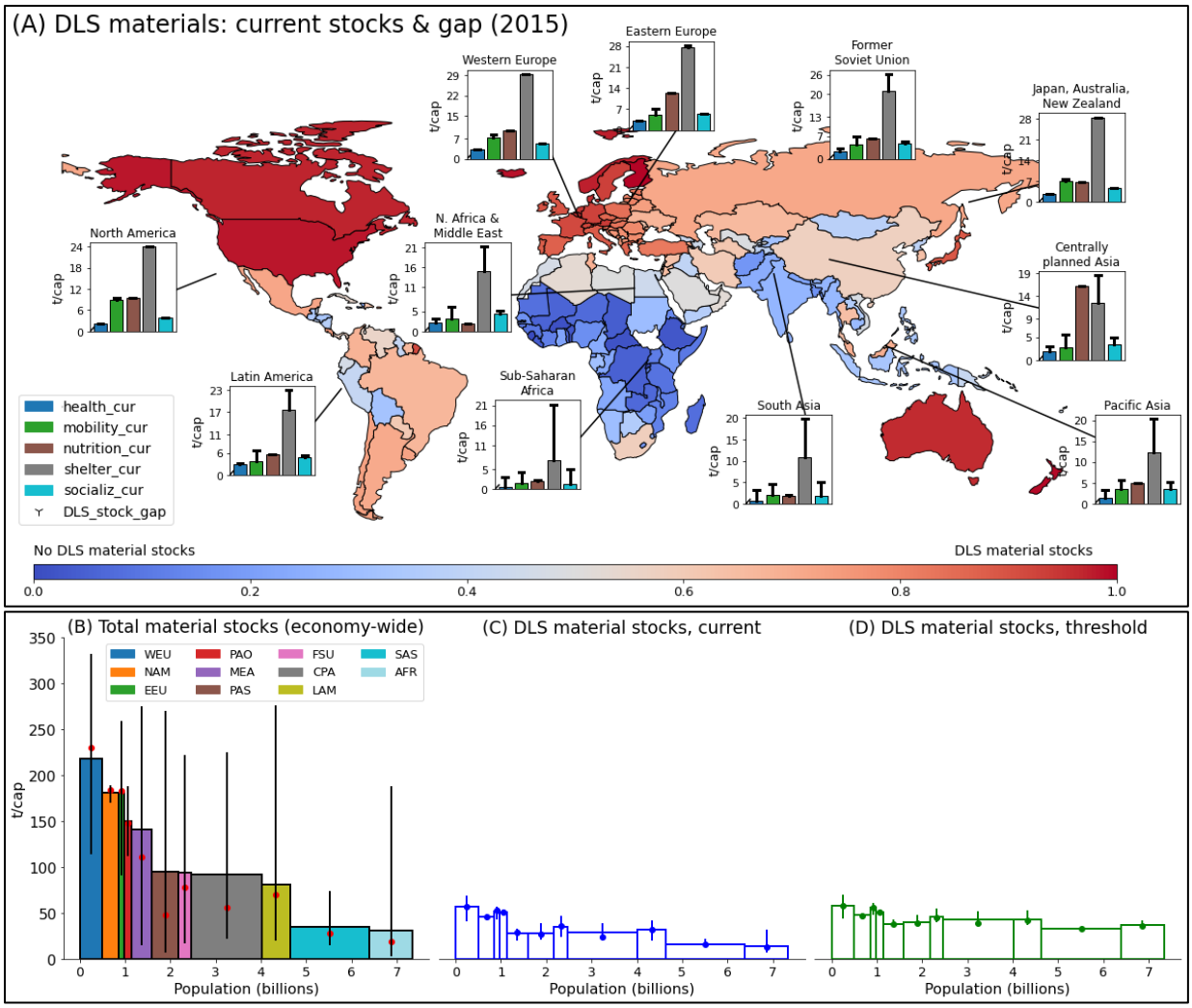

Figure 1: Preliminary Findings on Decent Living Standard material stocks around the globe. (A) Ratio of Decent Living Standard material stocks reached divided by threshold per country (colors indicate ratios), and Decent Living Standard material stocks reached versus apparent gap per R11 world-region by DLS dimension (small bar charts); (B) estimates of total, economy-wide material stocks (Wiedenhofer et al., in prep.a), (C) estimates of DLS material stocks, current (own estimate, bottom-up), and (D) estimate of DLS material stocks, threshold by world-region (own estimate, bottom-up). For panels (B-D), the bars show the mean-, the dot the median- and the vertical line the minimum- and maximum values of countries per region. AFR = Sub-Saharan Africa, CPA = centrally planned Asia, EEU/WEU = Eastern/Western Europe, FSU = Former Soviet Union, LAM = Latin America, MEA = North Africa & Middle East, NAM = North America, PAO = Japan, Australia, New Zealand, PAS = Pacific Asia, SAS = South Asia.

Material stocks for DLS & beyond-DLS services

The DLS material stocks to reach current and threshold DLS (Figure 2c-d) compared against estimates of total, economy-wide material stocks (Figure 2b), are small for the world-regions in the global North, North Africa & Middle East (MEA), and medium-sized for Pacific Asia (PAS), Former Soviet Union (FSU), Centrally Planned Asia (CPA), and Latin America (LAM), while for South Asia (SAS) thresholds are almost and for Sub-Saharan Africa (AFR) actually are larger than total, economy-wide stocks in 2015.

In comparison to per capita total, economy-wide stocks, the material stocks that would be required to close DLS gaps (threshold in Figure2d minus current in Figure2c) seem even

smaller. Calculating to global scale, the material stocks to close DLS gaps globally amount to 92 Gigatons (Gt), which are <10% of total, economy-wide stock estimates and three times the annual gross additions to stocks (processed material consumption for stock-building) in 2015 (34 Gt/a; data not shown).

Subtracting the average current DLS- from total economy-wide material stocks (per capita; Figure 2b-c) yields the material stocks that supply beyond-DLS services. These range between 99-161 t/cap for Europe, North America and North Africa & Middle East (MEA), 49-67 t/cap for Pacific Asia (PAS), Former Soviet Union (FSU), Centrally Planned Asia (CPA), and Latin America (LAM), and 18-19 t/cap for South Asia (SAS) and for Sub-Saharan Africa (AFR). For the regions with large DLS material stock gaps (Sub-Saharan Africa: 23 t/cap, South Asia: 17 t/cap) the lack of DLS stocks for many coincides with beyond-DLS stocks of roughly the same size, indicating large inequalities.

Towards finalization: ongoing work & next steps

On top of the presented results, the empirical work to answer all research questions is largely accomplished, requiring only minor improvements and clarifications across data sources and methods. To fully answer the research questions posed in the beginning, we are conducting the following steps over the coming weeks, to arrive at a complete manuscript for a pee-reviewed journal:

- Detailed quantification and visualization of the material flows that are required to close global DLS gaps at scale, and comparison to current annual material flows and beyond-DLS stocks (RQ2 at scale). This entails estimates of material flows required for targeted closing of DLS gaps, and estimates of the ‘rucksack’ of beyond-DLS material stocks that historically came with building DLS material stocks (RQ4). Work is in an advanced stage.
- Detailed quantification and visualization of beyond-DLS material stocks (RQ3) per product group (e.g. residential buildings, non-residential buildings, etc.). Work is in an advanced stage but requires further detailed data work for properly combining the system boundaries of top-down und bottom-up estimation approaches.
- Quantification of material stock thresholds via the top-down approach (methods section: b). Work on this point is largely accomplished but the meaningful integration with bottom-up DLS material stock estimates (interpretation) still requires refinement.
- Quantification of uncertainty. Calculations are prepared via data and code but need to be executed after a first full set of deterministic results are obtained. Additionally, the current

state of knowledge on resource use of DLS (from this work and literature review) will be discussed and synthesized for the paper during a writing workshop with co-authors on March 7-8th in Vienna at BOKU and IIASA (RQ5).

- Open Science: finalization of the supplementary information with methodological details and data and code underlying the results and figures.
- Submit the paper to a journal in Spring 2024.

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Material Cycles, Industry and Service Provisioning: A Review of Low Energy and Material Demand Modelling and Scenarios

Abstract

Developing transformative pathways for industry's compliance with international climate targets requires model-based insights on how supply- and demand-side measures affect industry, material cycles, global supply chains, socio-economic activities and service provisioning supporting societal wellbeing.

Herein, we review the recent literature modelling the industrial system for Low Energy and Materials Demand (LEMD) futures, resulting in lowered environmental pressures without relying on negative emissions. We identify 77 innovative studies drawing on nine distinct industry modelling traditions and critically assess system definitions and scopes, biophysical and thermodynamic consistency, granularity and heterogeneity, and operationalization of demand and service provision. We find large potentials of combined supply- and demand-side measures to reduce current economy-wide material use by -56%, energy use by -40 to -60%, and GHG emissions by -70% to net-zero. We call for strengthening interdisciplinary collaborations between industry modelling traditions and demand-side research, to produce more insightful scenarios and discuss research challenges and recommendations.

Keywords: climate change mitigation; sustainable resource use; integrated assessment modeling (IAM); ecological economics; industrial ecology;

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Krey	Volker	International Institute for Applied Systems Analysis and Norwegian University or Science and Technology	0000-0003-0307-3515	Investigation, validation, writing - review & editing
Akimoto	Keigo	Research Institute of Innovative Technology		supervision, funding acquisition
Grubler	Arnulf	International Institute for Applied Systems Analysis	0000-0002-6225-7712	conceptualization, supervision
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39

Summary points – highlight the central points of your review (max 8) in complete sentences.

- Modelling industry and service provisioning for Lower Energy and Material Demand (LEMD) is happening within all modelling traditions, and increasingly in interdisciplinary collaborations combining models and principles.
- Material cycles and stocks, as well as their dependence on energy use are usually not properly represented, except in those traditions focused on the biophysical basis of society.
- The granularity of industry and economic sectors, as well as materials differs substantially across traditions, with some input-output tables distinguishing up to 163 sectors and 69 materials.
- On the demand-side, up to ~10 end-use product groups are distinguished across modelling traditions, focusing on the groups of building and construction, transport, appliances and food. Less common but still prominent is modelling of functions such as square meter floor area or passenger-kilometers. Welfare and co-benefits beyond GDP are rarely addressed.
- Macro-economic traditions use endogenous economic growth theories to provide 'cost-optimal' pathways, incl. assumptions about autonomous efficiency improvements, regularly violating thermodynamics and ignoring or downplaying the 'costs' of escalating non-linear feedbacks, e.g., due to climate breakdown and ecosystem collapse in high growth scenarios.
- All other traditions use exogenous drivers such as population and economic growth and then simulate the technological, biophysical and behavioral GHG mitigation potentials of supply- and demand-side measures aiming to comply with emission reduction targets, however often excluding or simplifying macro-economic implications.
- We find a troubling lack of proper documentation and open data for more than half of the reviewed literature as well as a widespread lack of properly reporting model data inputs and model results, hindering comparability and evidence synthesis.
- We find various studies upscaling small-scale and/or static data to scenarios at national and global levels, which is a problematic oversimplification.

Future issues list – note where research may be headed (max 8) in complete sentences.

- Interdisciplinary combinations of modelling principles and traditions yield more robust, nuanced and policy-relevant insights, than any single tradition can provide.
- Thermodynamic and biophysical consistency at high granularity across material cycles, energy use and material stock turnover across industrial networks reacting to changes in final demand and socio-technological innovation is vital to understand time-dependent dynamics and efficiency potentials.
- Material stocks serve as constituents for service provision, as they are used to transform energy and material flows into functions and services in a context specific manner; what constitutes an acceptable and sufficient level of “low-demand“ is an open question requiring transdisciplinary approaches to derive justified targets.
- Widening the solution space for sustainable development and climate change mitigation by addressing a wider range of supply- and demand-side measures in combination is timely, utilizing optimization and simulation approaches drawing on a large set of possible measures beyond price-based instruments, acknowledging that LEMD transitions will induce dis-equilibrium, major structural changes and early retirement of some capital stocks.
- Assessing telecoupling in global supply chains is critical to identify potential rebound effects and burden-shifting, as well as economic winners and losers in LEMD transformations.
- Modelling should address the complex socio-ecological dynamics, feedbacks, and non-linearities inherent in LEMD transformations and the biosphere.
- Modelling should address the complex socio-ecological dynamics, feedbacks, and non-linearities inherent in LEMD transformations and the biosphere. The environment is more than a repository of resources to be extracted and a sink for waste and emissions. Complex trade-offs exist between different environmental aspects, ranging from the climate and biodiversity crisis to other Planetary Boundaries.
- Improved research infrastructure, open science principles, FaiR research and shared concepts and ontologies are needed to facilitate coupling of models, comparison of results and evidence synthesis.
- Connecting and contributing to ongoing efforts to improve the Shared Socio-economic Pathways (SSPs) framework is important so that future LEMD scenarios can be easily integrated into evidence synthesis by IPCC and others.

Terms and Definitions: definitions for max 20 most important abbreviations and key terms. 20 words max.

1. LEMD - Low Energy and Material Demand
2. Social Metabolism - Encompasses all materials and energy extracted and harvested, which are further processed, used and accumulated as material stocks by societies and their economies, necessarily resulting in waste and emissions
3. Material cycles and stocks - Physical flows from the extraction of raw materials to industrial processing and trade, to end-uses and accumulation as product stocks, resulting in (waste) by-products at each step as well as at the end-of-life
4. Material stocks - all long-lived in-use products utilized longer than one year, covering all socio-economically utilized products, machinery, buildings and infrastructure
5. Economy-wide - covering all economic production and consumption activities
6. System of National Accounts (SNA) – globally harmonized, socio-economic reporting system.
7. System of Environmental-Economic Accounts (SEEA) – globally harmonized, socio-economic and environmental reporting system.
8. SSP – Shared Socioeconomic Pathways: Set of scenarios used by the IPCC based on five narratives that describe plausible socioeconomic future trajectories
9. IAM – Integrated Assessment Model
10. ABM – Agent Based Model
11. SD – System Dynamics Model
12. MEFA – Material and Energy Flow Analysis, incl. dynamic stock-flow models
13. LCA – Life Cycle Assessment
14. PE – Partial Equilibrium macro-economic model
15. CGE – Computable General Equilibrium Model
16. MRIO – Multi-Regional Input-Output Model, covering the world economy

1) Introduction

This review addresses two concerns: Firstly, recent global assessment reports have clearly established that mitigating greenhouse gas (GHG) emissions and environmental impacts requires directly addressing the scale and composition of socio-economic material cycles and accumulated material stocks of buildings, infrastructure and machinery (IPBES, 2019; IPCC, 2022; UNEP-IRP, 2019). Improving energy efficiency and decarbonizing energy supply and industrial processes alone does not suffice to comply with internationally agreed upon efforts to limit the increase in global mean temperature to 1.5-2°C above pre-industrial levels (IPCC, 2022); furthermore, it does not address non-climate environmental impacts driving the transgression of five Planetary Boundaries (Richardson et al., 2023). Economy-wide material cycles include raw materials that originate from agriculture, forestry and mining and are processed by industry, manufacturing and construction; they include transport and waste management and, ultimately, final product demand, which accumulate as in-use material stocks (Haberl et al., 2019; Pauliuk and Hertwich, 2015). Material production and industry activity accounts for 20-34% of global GHG emissions (Hertwich, 2021; Lamb et al., 2021); material extraction is an important driver of land use change and biodiversity impacts (Giljum et al., 2022; UNEP-IRP, 2019). Crucially, recent reviews showed that many macro-economic Integrated Assessment Models (IAM) regularly violate the Laws of Thermodynamics and lack the granularity, resolution and framework to fully depict material cycles and material stocks (Bataille et al., 2021; Pauliuk et al., 2017; Stern, 2011). These gaps critically limit our understanding of the potentials, trade-offs and multi-SDG impacts of strategies aiming to reduce, slow and close socio-economic material cycles (Aguilar-Hernandez et al., 2018; Creutzig et al., 2022; Hertwich et al., 2019; Hickel et al., 2022; McCarthy et al., 2018; Muscat et al., 2021).

Secondly, global assessment reports have clearly established that expanding the solution space to demand-side measures and service provisioning is necessary (IPBES, 2019; IPCC, 2022; UNEP-IRP, 2019). Demand-side measures – defined as (Creutzig et al., 2021a): '*mitigation opportunities that involve individuals or industrial end users of products, services or processes.*' – aim to avoid, shift, and improve service provision to achieve Lower Energy and Material Demand (LEMD). (Wilson et al., 2022) state: "*Demand-side strategies change how services are delivered (e.g., more energy-efficient end-use technologies and infrastructure, digitalization, business models to increase efficient utilization of resources). […] Supply-side strategies change how resources are converted (e.g., precision agriculture, decarbonization of power production) [...]".*

Service provisioning for human needs and societal wellbeing can be grouped along material needs for food and water, mobility, shelter, thermal comfort and lighting, health, education, entertainment, social interaction and participation. All of these require material and energy flows as well as material

156 stocks of products, infrastructure and buildings, resulting in waste and GHG emissions (Fell, 2017;
157 Gough, 2015; Kalt et al., 2019; Lamb and Steinberger, 2017). Related research streams grounded in
158 different theories about society and social change include, for example, sufficiency (Jungell-Michelsson
159 and Heikkurinen, 2022; Sandberg, 2021), post-growth (Jackson, 2017; Hickel et al., 2021), steady-state
160 economics (O'Neill, 2015; Victor, 2022), sustainable consumption corridors (Fuchs et al., 2021), as well
161 as degrowth (Kallis et al. 2018; Hickel et al. 2022), and the circular economy (Aguilar-Hernandez et al.,
162 2018; McCarthy et al., 2018). Independent of one's favorite theory, LEMD substantially increases the
163 feasibility of addressing the climate crisis without relying on unproven large-scale negative emission
164 technologies, reduces the costs of mitigation and decarbonization, and contributes to improving
165 societal wellbeing (Creutzig et al., 2022, 2021b; Grubler et al., 2018b).

166 So far however, most climate change mitigation scenarios limiting climate heating to 1.5-2°C assume
167 unprecedented efficiency improvements and rapid decarbonization of energy supply and other
168 sectors, as well as gigantic amounts of negative emissions which is highly risky and prone to moral
169 hazards (Anderson and Peters, 2016; Minx et al., 2018; IPCC, 2022). Most mitigation scenarios also
170 assume endless economic growth and ever-increasing consumption, while perpetuating global
171 inequality (Hickel and Slamersak, 2022). Existing mitigation scenarios report hardly any reductions in
172 energy demand, partially because the underlying models lack heterogenous demand representations
173 and usually do not consider service provision (Edelenbosch et al., 2020). They therefore explore only a
174 narrow part of the solution space for sustainability transformations (Hickel et al., 2021; Keyßer and
175 Lenzen, 2021; Lamb and Steinberger, 2017). Recently, the seminal 'Low Energy Demand (LED)' scenario
176 with high service provisioning globally (Grubler et al., 2018b), as well as the dedicated IPCC chapter on
177 services, demand and social aspects of mitigation (Creutzig et al., 2022) kick-started research into
178 viable 'low-demand' futures with high wellbeing around the world, without resorting to technological
179 silver-bullets.

180 This review addresses these concerns by surveying recent innovations in models aiming to address
181 material cycles and stocks, industries, energy supply and GHG emissions, as well as final demand and
182 service provision. We focus on Lower Energy and Material Demand (LEMD) scenarios and the
183 underlying models. We do not aim for a general synthesis of mitigation potentials, which was recently
184 done by (IPCC, 2022). *Herein, we summarize the status and research needs for modelling material*
185 *cycles and industry in LEMD scenarios, answering the following research questions:*

186 • *Which aspects, principles, and system linkages of material cycles and industry need to be covered*
187 *for LEMD scenarios and how are they addressed in the literature?*
188 • *How is service provisioning and its link to industry conceptualized and operationalized in the recent*
189 *and relevant modelling literature?*

- *Which potentials of supply- and demand-side measures for LEMD have been shown so far?*
- *Which recommendations for modelling industry and material cycles for LEMD scenarios emerge?*

Literature deemed relevant was identified between 03/2022-09/2023 from scientific literature databases and via citation snowballing, to identify fully relevant and innovative studies, which aim to a) have biophysical and thermodynamic consistency between material cycles and stocks, energy use and GHG emissions, 2) treat industry not as end-user but as delivering to intermediate and final demand, 3) model demand and service provisioning ideally in non-monetary units, and 4) model scenarios with low(er) demand. We focused on recent, noteworthy studies published between 2014-2023, screened over 300 studies and selected 75 for in-depth review. We grouped all included studies according to their main modelling tradition, and assessed model scopes and results detail, including their operationalization of "service provisioning", using the Energy Service Cascade (Kalt et al., 2019) and the Stock-Flow-Service Nexus (Haberl et al., 2017) as analytical frameworks. Additional documentation about the research design and methods, as well as the full assessment of studies can be found in the supplemental information and data file.

2) Principles and purposes of the nine modelling traditions

We identify nine industry modelling traditions, each developed for specific purposes and based on different worldviews, theories, and modelling principles (Figure 1). For an introduction and overview for each tradition, we refer to the supplemental information section 2. These different foundations result in diverse terminologies, system definitions, model scopes and aims, data requirements, and computational complexity. Modeling society-nature interactions began in the 1960s, spurred by concerns about environmental degradation, energy security, and climate change, and the establishment of UNFCCC and IPCC. Macro-economic IAMs were developed to simulate emission scenarios and mitigation strategies, grounded in fields such as Energy- and Environmental Economics (Figure 3, in green). Alternative socio-ecological approaches focusing on a biophysical, non-monetary systems perspective emerged between the 1960s and 1990s, grounded in fields such as Industrial Ecology, Sustainability Science, Ecological Economics, and Complex Systems Science (Figure 3, in yellow).

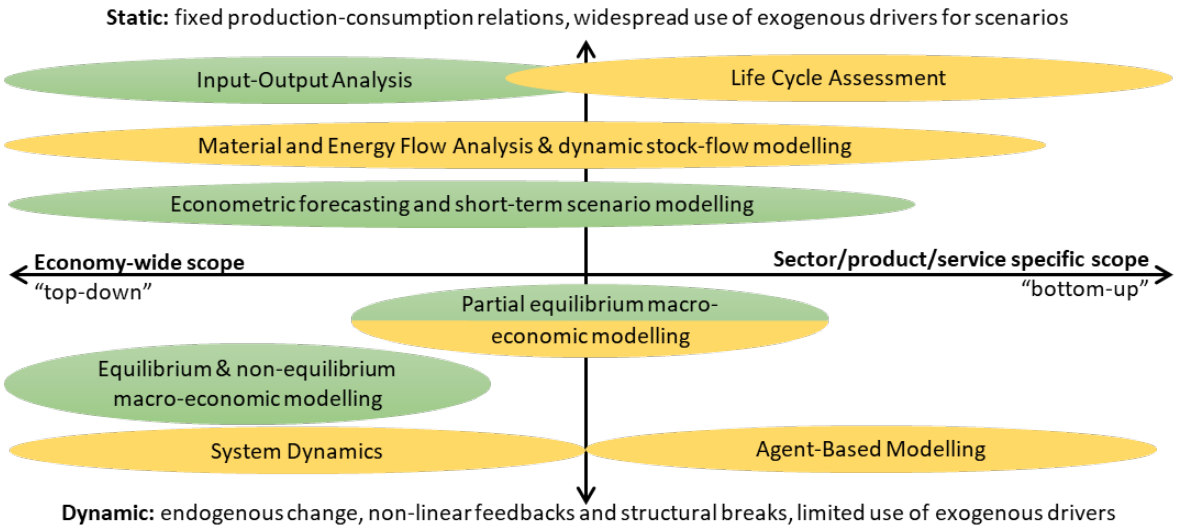

Figure 1: Foundational principles and typical scopes of the nine modelling traditions reviewed herein. Traditions in green originate from Energy and Environmental Economics, while yellow traditions originate from Engineering, Industrial Ecology, Ecological Economics, Socio-Metabolic Research and Complex Systems Science. The positioning of each tradition is based on the authors domain expertise and is only meant to provide orientation. We refer to the supplementary information for a more detailed discussion and literature sources for each tradition.

3) State-of-the-art models for LEMD scenarios

We identified 77 relevant studies published between 2014 – 2023. Two-thirds operate within their tradition, while one-third combines methods and data from engineering, Industrial Ecology, Ecological Economics and Complex System Sciences ('biophysical+'), ABM and other traditions ('ABM+'), as well as biophysical and macro-economic modelling ('economic+biophysical'; Fig.2a). Most studies have national, world-regional, or global scopes (Fig.2b). Two-thirds of regional and (sub)national studies focus on the Global North, while only one-third specifically investigates the Global South (Fig. SI-3). Around two-thirds of the reviewed studies are published Open Access and have supplementary information (Fig.2c). Only one-third provides machine-readable supplementary data and a mere 10 studies (13%) provide open model code, hampering assessment, comparison and evidence synthesis.

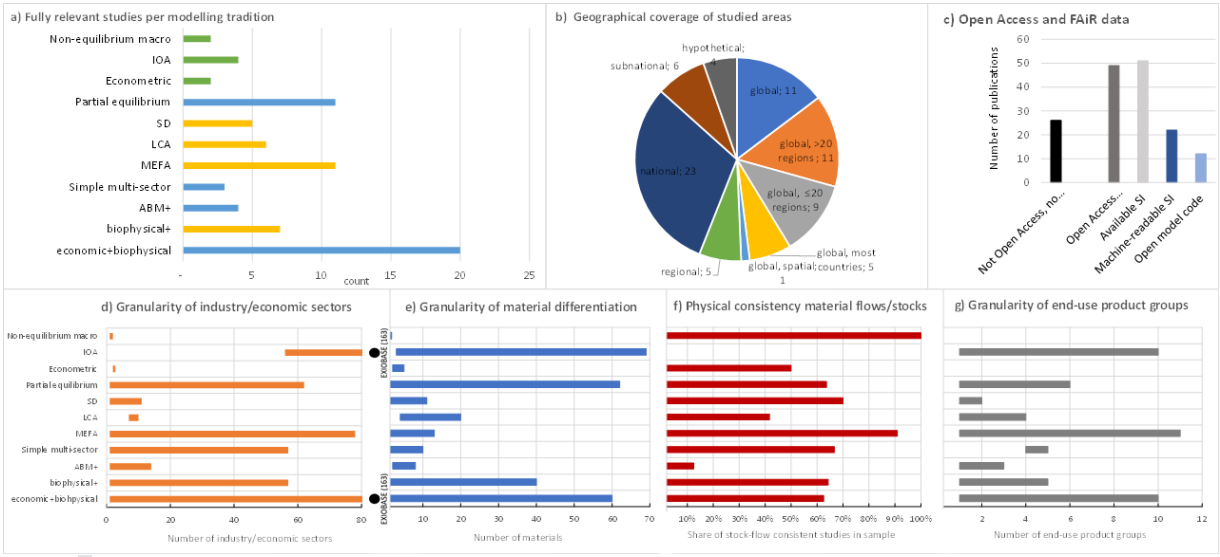

Figure 2: Overview of relevant studies by tradition and emergence from original research fields (a) coverage of geographical scopes (b), and implementation of FAiR open science principles across the reviewed literature sample (c). Ideally, studies, results and model code should be Findable, Accessible, interoperable and Re-usable (FAiR)(Wilkinson et al., 2016). Further documentation on coding and assessment can be found in the supplemental information section 2.

We find substantial differences in the resolution and granularity of industries and economic sectors modelled across the traditions (Fig.2d). Especially MRIOs and those using underlying data stand out, as they have been specifically developed to provide detailed sectoral classifications for extractive, manufacturing and service industries, with EXIOBASE at 200 products or 163 industries (Stadler et al., 2018), and GLORIA with 120 sectors (Lenzen et al., 2021). Others like WIOD or GTAP have lower resolution of 35-64 sectors. Models from the MEFA, LCA and SD traditions usually focus on specific industries and/or materials, resulting in relatively lower sectoral resolution, although recent synthesis studies compiled high resolutions of up to 78 industries/sectors. For the macro-economic traditions, we find an intermediate sectoral resolution of 1 – 57 sectors.[1]

MRIOs (69), partial (62) and general (60) equilibrium models, as well as model combinations using input-output tables (biophysical+, economic+biophysical) are most detailed in covering materials. Depending on scope and aims, some of these studies aggregated to only 1-3 materials (Fig.2e). For the other traditions, we find low (1-8) to intermediate (10-20) materials granularity. Regarding biophysical stock-flow consistency, we find that both non-equilibrium studies model material stock-flow relations, however only stylized. For MEFA, biophysical consistency is the core principle (some MEFA studies only look at either stocks or flows though). In contrast to the relatively higher resolution and granularity found for MRIOs, we find that they only partially comply with biophysical stock-flow consistency (Fig.2e): while environmentally-extended input-out analysis enforces mass-balances, it

[1] Please note that the granularity of some studies based on LCA/MRIO combinations, which have substantial sectoral resolution in their 'background system', could not be assessed due to lacking documentation of the aggregation and truncation decisions common in LCA.

does not account material stocks, only specific variations account waste-by-products (waste and physical input-output analysis), and limitations arise from combining monetary and mass units (Streeck et al., 2023a). Regarding the coverage of modelled end-use product groups, we find that MEFA, MRIO and combinations of economic and biophysical traditions cover the most with between 10-11 end-use products groups (Fig.2f). Studies of the non-equilibrium macro and econometrics traditions do not model the number or material cycles of products explicitly, but depict resource use as intensity of macro-economic variables (e.g., per unit of aggregate or sectoral GDP).

When it comes to service provisioning, we find that across all studies what is most often modelled are end-use product stocks (amounts, weight, …) of appliances, food, motor vehicles, construction and residential buildings (Figure 3a). In summary, 'building & construction' is most often covered, followed by 'transport & vehicles'. For actual functions as physical 'action', the most prominent categories are housing, passenger transport, nutrition, heating and cooling, non-residential floorspace and freight transport (Figure 3b). Services as 'what is actually demanded' are substantially less quantified, mostly via employment and Decent Living Standards (DLS) (Figure 3c). Welfare, well-being and co-benefits are often approximated via GDP (Figure 3d).

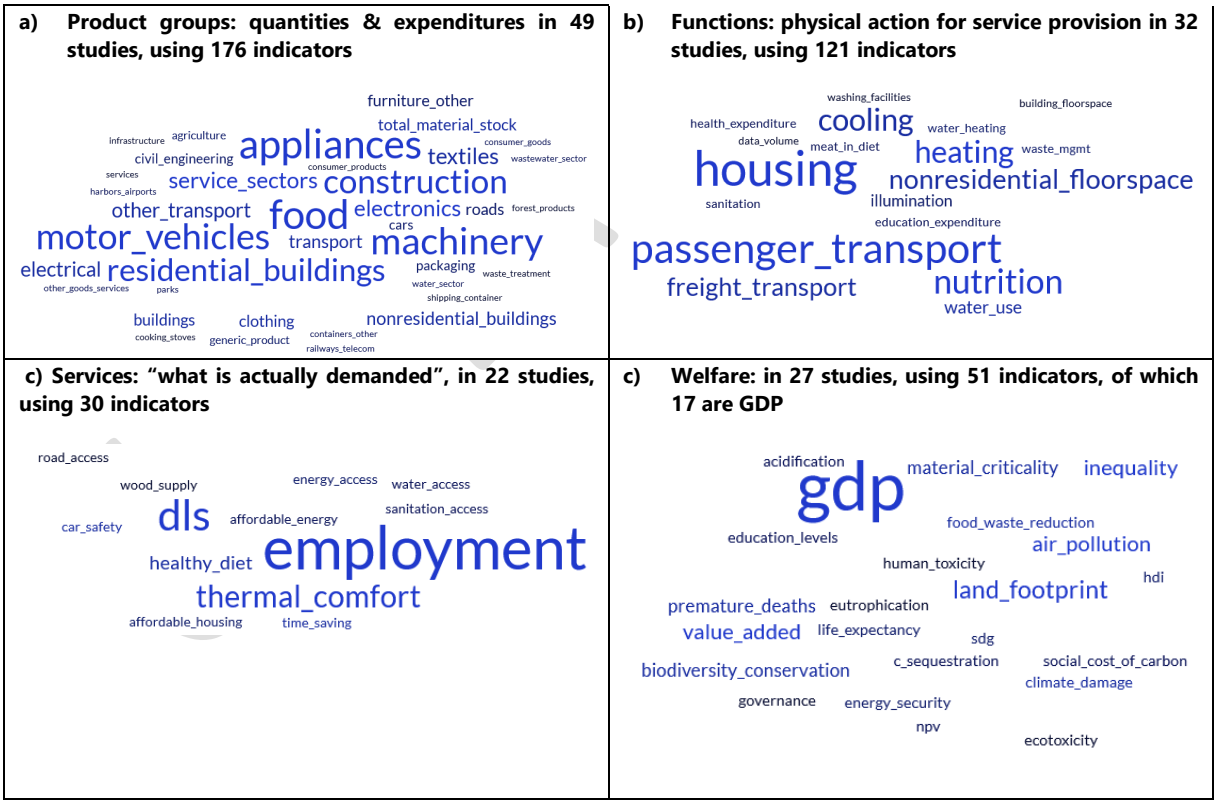

Figure 2: Indicators for product groups, functions, services and welfare & co-benefits used in the reviewed literature. For this grouping, we draw on the Energy Service Cascade (Kalt et al., 2019)*. We add welfare & co-benefit indicators which are defined at macro-level. For details on the definitions, accounting methodology of the cascade elements, and counts by item please see supplemental information section 2.*

3.1. State-of-the-art in non-equilibrium LEMD modelling

We identify substantial novelty in the emerging field of stock-flow consistent (SFC) Ecological Macro-Economics, which so far has mainly dealt with energy and GHG emissions (Jackson and Victor, 2020; Jacques et al., 2023; Nieto et al., 2020). These studies aim to use thermodynamically appropriate production functions including energy/exergy and materials, also complying with stock-flow consistency. Extending model scopes to material cycles has begun for global transport and the transition to electric vehicles (Pulido-Sánchez et al., 2022) and in a global IAM approach (Capellán-Pérez et al., 2020). This research line seems highly relevant for LEMD scenarios. See supplemental information section 4 for a detailed discussion of each study.

(Dafermos et al., 2017) apply the post-Keynesian, Stock-Flow-Consistent (SFC) approach with Georgescu-Roegen's flow fund model to the global economy. Highly innovatively, this model explicitly formalizes monetary and physical stocks and flows, complying with financial accounting rules and the Laws of Thermodynamics. The model encompasses material extraction, recycling, energy use, and GHG emissions in a stylized semi-empirical manner, used in exploratory scenarios. Similarly, (King, 2020) presents a stylized model with monetary and biophysical stock-flow consistency (SFC), implemented in System Dynamics using Input-Output Tables. They consider a finite, regenerating natural resource and energy availability already in their production functions, which indirectly constrains output due to its essential role for capital operation and sustaining the population, as well as labor availability constraints. Data-rich applications of the MEDEAS model built on these principles have been presented for electric vehicles (Pulido-Sánchez et al., 2022) and for a global IAM study (Capellán-Pérez et al., 2020).

3.2. State-of-the-art in Environmentally-Extended Input-Output Analysis LEMD modelling

IO studies usually exogenously impose reductions and shifts in final demand, using the static, demand-driven Leontief production function to model industry's responses. Sectoral granularity is medium to high, depending on the choice of the multi-regional input-output model (MRIO). Economy-wide feedbacks are ignored, e.g., under-utilized capacity, (un)employment, industrial structural change (including industry material stocks), marginal technology adoption. Interactions between sectors and final demand are typically expressed in monetary terms. Rarely physical waste by-products in production are modelled, using hybrid IO technique of 'waste input-output analysis' (Nakamura and Kondo, 2009). However, substantial limitations exist, because statistics on industrial waste by-products and end-of-life waste suffer from considerable quality issues (Tisserant et al., 2017). Hybrid approaches combining MRIO with LCA are used for comprehensive supply chain coverage and detailed process

representation, however due to high time and data requirements, this is usually only applied to specific products/industries/technologies. Next steps for EE-IO include better representing secondary materials processing and recycling, improving the robustness of IO tables esp. for the Global South, representing novel technologies and sectors, dynamic modelling of future industrial structures, including production capacity and material stock models; and developing physical IO models (Bruckner et al., 2019; Wieland et al., 2022). These steps will improve material stock-flow consistency beyond price assumptions, and enable linking production explicitly to service provisioning, rather than via monetary final demand alone. See supplemental information section 4 for a detailed discussion of each study.

The reviewed studies start by developing changes to final demand, based on stakeholder workshops on sufficiency and green consumption (Vita et al., 2019), the SDG target on access to 'all-season' mobility infrastructure (Wenz et al., 2020), hypothetical product light-weighting, lifetime extensions, and improved recycling (Donati et al., 2020; Wiebe et al., 2019), and food waste reductions (Garvey et al., 2021) (Hayashi et al., 2022). Some change the fixed Leontief 'production recipe' (input-output coefficients), while others hold them constant, to model the resulting economy-wide material and energy use as well as GHG emissions. Detailed LCA data is sometimes used to either disaggregate sectors, or translate specific measures into more aggregate sector and final demand categories available in an IO model.

(Gast et al., 2022) conduct a highly innovative global assessment of supply-side industrial symbiosis potentials for steel, cement, paper, and aluminum industries for the year 2017, hybridizing MRIO with MEFA. They find that even major changes to by-product utilization from cement production yields -7% GHG mitigation potentials. If industrial symbiosis is to be promoted, the top priorities are intensified utilization of other cementitious materials and flue gas heat recuperation for electricity generation and heat exchange.

3.3. State-of-the-art in econometric modelling and forecasting

The main strength of this approach is that it does not rely on restrictive assumptions regarding agents and firms' behavior. Three key limitations for LEMD modelling exist: models display high path-dependency and often require complementation with other models. Often simplified stock-flow dynamics are used, depicting materials-oriented measures only through changing demand-price elasticities. Energy use and rebound effects driven by general equilibrium dynamics are often not accounted for, potentially overestimating low demand potentials.

(Pollitt et al., 2020) employ the E3ME model to assess the impact of materials taxation for the carbon-intensive sectors basic metals (steel, aluminum) and cement. They draw on material use rates from

MFA (Pauliuk et al., 2016) to estimate sector unit costs and modify input-output coefficients and impose exogenous assumptions about energy intensity. They show that a €80/tCO2 materials tax reduces the EU's energy-related emissions by 6% and process emissions by up to 40%, without carbon leakage, with minimal GDP impacts and slight employment reductions.

(van Ruijven et al., 2016) 2016 rely on carefully selected regression models to build a relatively detailed bottom–up steel and cement model embedded in a long-term global energy system model. They generate future projections of steel and cement demand based on the SSP2 scenario. While they show rapid increases in absence of climate policies, by 2050 steel and cement demand can decrease by 80–90% and 40–80% below 2010 level if a carbon tax of 100 $/tCO$_2$ + 4%pa is imposed. Yet, availability of CCS plays a major role.

(de Souza and Pacca, 2023) evaluate the CO2 mitigation potential of circular economy strategies considering jointly the cement and steel industries in Brazil: recycled-based EAF and charcoal-fired BF in the cement industry; material efficiency, the substitution of supplementary cementitious materials for clinker and the substitution of petroleum coke with alternative fuels. They show that together, circular practices and industrial symbiosis can avoid 52% of the business-as-usual emissions up to 2050 at US$ 10/tCO2e.

A highly innovative and notable effort not yet addressing material cycles explicitly is the MARCO-UK model, first energy-economy-wide model to include thermodynamic (energy) efficiency, and the useful stage of energy consumption (as useful exergy). For example, (Sakai et al., 2019) use MARCO-UK and show that around a quarter of historical UK economic growth since 1970 could be attributed to gains in economy-wide thermodynamic energy efficiency.

3.4. State-of-the-art in equilibrium-based macro-economic LEMD modelling

This tradition usually models lower demand only compared to a growth-oriented business-as-usual scenario; see supplemental information section 4 for a detailed discussion. Most do not find actual absolute LEMD reductions, which is often confusingly communicated by mainly reporting modelled ‘reductions’ vis a vis a questionable growth BAU scenarios. In the simplest form, elasticities for materials-producing and using sectors are modified exogenously (Zhang et al. 2022). More innovatively, models are extended with the production of specific materials or raw material extraction, however without biophysical consistency across material cycles and stocks (Nong et al., 2023; OECD, 2019; Schandl et al., 2020). Those studies report that even highly ambitious, supply-side resource efficiency and climate change mitigation measures result in a +50-100% increase of global resource use, driving further ecological deterioration. Interestingly, (Nong et al., 2023) nest Leontief production functions into widely used CES functions by introducing 'technology bundles' for three key industries—

steel manufacturing, land transportation, and electricity generation, consisting of various technologies using distinct combinations of inputs, capturing practical constraints in substituting labor and capital between technologies, at least in the short-term. Material stocks and service provisioning are usually not included in non-monetary units, except when combined with an explicit material stock turnover model from the MEFA tradition (Cao et al., 2019). They assume perfect factor allocation, full capacity utilization and rational agents ('homo oeconomicus'), which is questionable, esp. because LEMD probably results in under-utilized capacities, dis-equilibrium due to oversupply, e.g., fossil fuels and products using them, as well as early decommissioning of stranded assets. Widely used CES industrial production functions assuming full substitutability of energy violate thermodynamics, ignoring that final energy/exergy are complements in industrial production (Keen, 2021; Keen et al., 2019; Stern, 2011). Introducing full thermodynamic consistency for material cycles, energy use, material stocks, as well as extending service provisioning beyond monetary valuation are required.

CGEs can also be combined with dynamic MEFA to explicitly and biophysically model stock-flow dynamics. (Cao et al., 2019) combine a CGE model with a dynamic MEFA for residential buildings in China, considering service and stock saturation (m^2 per capita). Modelled construction material use feed into their CGE model to quantify economy-wide effects, ensuring both biophysical and monetary consistency. Exogenously assumed lower building service saturation levels and delayed stock development could save 25.4 Gt in embodied CO2 emissions in the construction sector, partially offset by economy-wide rebound effects of 18.8 Gt, assuming GDP remains constant and is re-distributed to other sectors. (Tong et al., 2022) investigate global shifts from internal combustion engines to battery electric and fuel cell vehicles, covering supply and demand for platinum group metals and GHG emissions, combining the IMED CGE with a dynamic MEFA for cars. They model several scenarios for future car stock saturation levels, structured via Multi-Level Transitions Theory. They highlight potential future mismatches between platinum group metals extraction, vehicle production, and end-of-life vehicles for recycling.

Highly innovatively, (Bachner et al., 2021) extend a CGE by explicitly modeling service demand using non-monetary indicators, construct an alternative wellbeing indicator, and quantify co-benefits and avoided burdens, for Austria. They model measures avoiding, shifting and improving demand for buildings and transport. They use an energy-focused building vintage model (m^2 of floor area), and represent transport modes and travelled distances, which are later converted to monetary units via stock-flow-service relations. Their alternative wellbeing indicator covers monetary welfare effects for private and public consumption, co-benefits such as avoided air pollution incl health impacts, and changes in leisure. In their ambitious climate transformation scenario, they find GDP to decline slightly, while societal welfare increases.

3.5. State-of-the-art in partial equilibrium LEMD modelling

PE sector models are technology-rich optimization models built on thermodynamic consistency for their respective sector, with exogenous demand either from GDP, population or specific material/energy demand dynamics using econometric methods, and often assumed automatic material and energy efficiency gains. PE models are increasingly combined with models from other traditions, especially for modelling demand for energy services, which has been presented at high granularity using physical service provisioning indicators (Gaur et al., 2022). PE often draws on data from other traditions, such as LCA, engineering, or industrial ecology, requiring complex and time-intensive data harmonization. Usually, there are little considerations of rebound effects (van den Berg et al., 2019). Future decoupling of economic growth from energy and material needs to be exogenously assumed. It is so far unclear, if a high level of detail for consistent service and material demand in PE IAMs is feasible, or if soft-coupling with other models or innovative multi-model analysis like e.g., applied in (Gaspard et al., 2023) is more advantageous. See supplemental information section 4 for a detailed discussion of each study.

(Grubler et al., 2018a) present the groundbreaking Low Energy Demand (LED) scenario, covering service provisioning not only for energy services but for thermal comfort, consumer goods, mobility, food, commercial and public buildings, as well as upstream freight transport and industry activities, quantified at the global level via the hybrid MESSAGEix-GLOBIOM model. The scenario combines reduced energy and material demand with substantially increased supply chain and end-use service provisioning efficiency, finding that final energy demand could decrease by - 40% until 2050. Focusing on one country, (Barrett et al., 2022) report a reduction of -52% in energy demand by 2050 compared to 2020 in the UK, resulting from technical and behavioral measures without compromising wellbeing. To consistently represent all services, they enrich the macro-economic model TIMES using an MRIO, apply dynamic MEFA for construction, buildings and the food industry, and a bottom-up transport model. In this 'whole-systems' model, industry interacts with transport services, construction, building stocks and their lifecycle, and nutritional requirements, as well as endogenous economic growth. A high level of detail for options to 'improve' energy efficiency, 'avoid' energy use and 'shift' to more efficient energy demand provision can be covered. Also modelling lower energy service demand for one country, (Oshiro et al., 2021) find a potential of -37% reduction in final energy demand by 2050 for Japan. They apply the technology-rich PE energy systems model AIM/Enduse for Japan, which is exogenously driven by GDP and population and as their industry sector is not linked to final demand, dematerialization and material efficiency factors (elasticities) are exogenously modified and no material cycles or stocks are depicted.

There are attempts to extend PE IAM models for an improved material representation either focusing on specific sectors like steel and iron (Zhang et al., 2019), food (Springmann et al., 2018), forests (Daigneault et al. 2022) or materials like plastics (Stegmann et al., 2022) or on specific measures like e.g., a global transition to autonomous shared vehicles quantifying operational and industrial energy use, basic materials (cement, iron/steel, plastics) and GHG emissions (Akimoto et al., 2022). There are also attempts to incorporate ores and metal extraction and processing sectors, typically absent in PE models, incorporating material availability constraints over time, addressing measures such as technology lifetime extension, recycling, and material intensity reduction (Tokimatsu et al., 2018). They find that metal requirements vary significantly across scenarios and uncertainties, with some metals, including Vanadium, consistently deemed critical. Combining dynamic MEFA with a PE leads to stock-flow consistency, which increases the credibility for medium- to long-term projections of structural change and material availability, in particular. (Kermeli et al., 2022) find steel demand for 2100 to be -75% lower than in flow-based estimations when explicitly modeling steel stock-flow dynamics, incl. end-of-life recycling and assumed per capita saturation of stocks. (Lechtenböhmer et al., 2015) assess how re-industrialization and energy-intensive industries can be aligned with the German Climate Protection Law. The study employs a technology-rich energy systems PE model and a simplified stock-flow MEFA model. Re-industrialization could impede Germany's energy and GHG targets due to limited efficiency potentials, requiring further demand-side measures. (Deetman et al., 2021, 2020, 2018) combine an IAM with dynamic stock-flow MEFA endogenously modeling global material requirements for electricity, buildings, vehicles and appliances under climate policy scenarios. Innovatively, this approach provides biophysical consistency between the demand for service provisioning, material cycles and stocks, including repercussions for industry.

Two multi-model studies driving PE energy system models with exogenously driven demand from other modules and/or demand-side measures are also identified. (Costa et al., 2021a) soft-couple PE, LCA, MEFA and MRIO modelling to assess European net-zero pathways. They find that behavioral changes could contribute -20% of the GHG reductions needed for net-zero by 2050. (Günther et al., 2019) combine resource efficiency and demand-side measures to model net-zero pathways for Germany. They present a technology-rich multi-model analysis driven by exogenous assumptions for sub-modules for transport, heating and cooling in buildings, agriculture and forestry, which then drive a PE energy optimization model, a waste module, and a global trade model. The most ambitious scenario combining phase-outs, supply-side efficiency and technological progress with demand-side measures shows that until 2050, GHG emissions can be reduced by -95%, raw material consumption by -56% and final energy consumption by -24%.

3.6. State-of-the-art in System Dynamics LEMD modelling

We find several studies integrating environmental, biophysical, economic and social considerations. System Dynamics models simulate dynamic interlinkages between multiple evolving parts of a system. The complexity and traceability of models limits system expansion, their simulation approaches are validated on historical relationships, and the structures of the models can limit which scenarios can be modeled, or would require exogenously overruling parts of the dynamic system. More systematic coverage of material cycles, stocks and esp. service provisioning could make this tradition highly interesting for LEMD scenarios. See supplemental information section 4 for a detailed discussion of each study.

(Allen et al., 2019) simulate supply- and demand-side measures for Australia, incl. economy-wide raw material extraction, final energy, and selected material stocks. Their 'Sustainability Transition' scenario achieves 70% progress towards the SDGs by 2030, while focusing either on economic growth, social inclusion, or green economy strategies achieves limited progress. (Moallemi et al., 2022) model low-demand pathways to achieve the SDGs, depicting service provisioning and socioeconomic wellbeing via a capability's perspective, and use life expectancy and the Human Development Index as headline indicators. Industry and the economy are only represented via aggregate Cobb-Douglas production functions. They find that multiple early interventions are necessary to facilitate long-term SDG progress after 2030. (Neumann and Hirschnitz-Garbers, 2022) quantify how a 100% renewable energy system globally impacts material reserves and utilization of bulk- and precious metals. They find that improved recycling can reduce potential economic constraints due to the depletion of high-grade raw material reserves. (Sverdrup and Olafsdottir, 2023) extend the World7 IAM with complete cement, sand and metal cycles, incl. energy use and GHG emissions, complying with mass and energy balance. Their low-demand scenario assumes a global stabilization and then decline of concrete stocks per capita, low carbon energy and industrial processes, as well as improved recycling and material substitution.

(Kumar et al., 2021) present a noteworthy and innovative model of the energy and materials required to achieve development goals in India, e.g., food and water security, housing and clean energy for all, sufficient healthcare and access to clean cooking and transport. Sectoral growth is also driven by a soft-linked CGE model to ensure macro-economic consistency. Highly innovatively, they explore how urban built form shapes housing and transportation resource and energy demand.

3.7. State-of-the-art in Life Cycle Assessment LEMD modelling

Using detailed LCA for system-level modelling and LEMD scenario analysis requires methodological advancements and models from other traditions to overcome typical limitations, especially of

attributional LCA. Recent advances include consequential LCA, as well as upscaling through combining LCA with dynamic MEFA and its stock-flow models. See supplemental information section 4 for a detailed discussion of each study.

(Verhoef et al., 2018) estimate the energy savings potential of additive manufacturing across multiple sectors using attributional LCA, and find substantial technical energy saving potentials, not considering rebounds nor shifts in demand. (Van der Voet et al., 2019) combine consequential LCA with a stock turnover model to assess metals production and recycling for future energy scenarios. They find that increasing secondary metals use could reduce life-cycle emissions substantially at the global level, but only in the second half of the 21st century when end-of-life metals increasingly become available from ageing material stocks. (Buschbeck and Pauliuk, 2022) use consequential LCA to assess when substituting emission-intensive materials with timber leads to net GHG savings, considering that growing forests are also natural carbon sinks. They find that short term (<25 years), intensive wood harvest is not climate beneficial, while long-term potentials depend on the speed of energy system- and industrial decarbonization.

An important contribution to LEMD futures is the modelling of the required resources and emissions for sufficient consumption, 'just' access to basic services, and DLS, using LCA. (Bjørn et al., 2018) use a hybrid of attributional LCA and MRIO to estimate the climate impact of surveyed household consumption baskets for ten service demand areas in Denmark, finding required reductions of supply- and demand-side emission intensities by factor 2-14 to comply with climate targets. (Rammelt et al., 2022) estimate life-cycle impacts of 'just access' to energy, water, food, housing and transport drawn from SDG indicators globally, and eclectically combine attributional static LCA factors. In 2018, eradicating severe deprivations could amount to 2–26% additional impacts on climate, water, land, and nutrients, amounting to similar impacts induced by the wealthiest 1-4%.

Recently, research on DLS has proliferated, with studies addressing a common set of products and services required for Decent Living, including housing, mobility, and nutrition, for some Global South countries (Mastrucci et al., 2020; Mastrucci and Rao, 2019; Rao et al., 2019) and globally (Jarmo S. Kikstra et al., 2021; Millward-Hopkins et al., 2020). Detailed LCA inventories for the DLS dimensions are directly linked to the use of materials and stocks by households, MRIO-based footprints address truncation errors and dimensions where the linkage with materials is less clear (nutrition, education, healthcare, and socialization), and IAMs such as MESSAGEix-GLOBIOM can be used to estimate impacts from energy supply and decarbonization. Food and transport dominate energy for decent living, while housing dominates upfront energy investment needs; in sum, 149-156 EJ/year of final energy would be needed after 2040, ~60% less than today (Jarmo S. Kikstra et al., 2021; Millward-Hopkins et al.,

2020). Nutrition and mobility at DLS globally would require 6 t/cap tons of raw materials, and stocks of ~43 t/cap in buildings, infrastructure and industrial assets (Vélez-Henao and Pauliuk, 2023).

3.8 State-of-the-art in dynamic Material and Energy Flow Analysis LEMD modelling

Dynamic MEFA focuses on a thermodynamically consistent representation of material cycles and material stocks at national to global scales, either for sectors or materials, usually treating socio-economic dynamics as exogenous. A rapidly growing number of studies investigates how lower demand for material product stocks is a crucial demand-side measure, which combined with material efficiency, circular economy strategies, technological improvements in industry and energy system decarbonization can achieve 1.5-2°C compatible pathways. For this purpose, dynamic stock-flow modelling is often combined with energy statistics, LCA and EE-IO to model supply chain energy use and GHG emissions. First combinations with macro-economic models are also identified. See supplemental information section 4 for a detailed discussion of each study.

A common approach is to study the technical potential of reducing turnover across the entire material cycle, by combining possible technical changes in all process steps, including manufacturing (light-weighting and less scrap), longer and more intensive use, and better re-use and recycling (Ciacci et al., 2020; Kalt et al., 2022; Pauliuk et al., 2021; Song et al., 2023; Wang et al., 2022; Watari et al., 2022; Zhang et al., 2018). In those studies, material cycles and stocks are linked to energy use and GHG emissions, enabling thermodynamically consistent modelling of GHG mitigation potentials from materials-oriented strategies. As (Krausmann et al., 2020) show for 2015, ~40% of global energy use and GHG emissions were required by industry, transport and construction for stock-building, and ~60% for stock utilization and service provision.

In addition, it is common to exogenously assume lower stock growth or lower stock saturation levels in the future, which inevitably leads to lower material and energy demand, although with substantial delays (Zhou et al., 2022) (Watari et al., 2022) (Watari et al., 2020; Watari and Yokoi, 2021) (Krausmann et al., 2020) (Cao et al., 2020) (Cao et al., 2021) (Pauliuk et al., 2021; Zhong et al., 2021) (Kalt et al., 2021) (Ciacci et al., 2020). Saturated/stabilized material stocks, combined with longer lifetimes and high recycling would drive substantial reductions of raw material extraction and subsequent energy use. The socio-economic feasibility of lower in-use stocks is, however, assumed and not endogenously modelled nor explained. These scenarios therefore show the extent to which demand-side reductions would be needed to comply with global climate targets, under realistic supply-side improvements and industry decarbonisation pathways.

Dynamic MEFAs are also used to model land-use and the industries extracting and processing biomass for food, feed, biofuels, material use and as potential carbon sinks. (Mayer et al., 2022) model the

578 European food and land-use system, combining dynamic MFA and consequential LCA. Several low
579 demand scenarios explore alternative diets and variable non-food product demand for biofuels and
580 material use. They find that agroecology can mitigate some emissions, but only if combined with less
581 meat consumption, a smaller-sized agri-food system, and if livestock systems are better aligned with
582 regional feed production capacities. (Bailis et al., 2015) quantify the carbon emissions due to pan-
583 tropical woodfuel supply and demand for subsistence cooking and commercial uses, using spatially-
584 explicit information on supply, travel distances and demand. They find that 27-34% of woodfuel
585 harvested exceeds annual biomass regrowth, resulting in ~2% of global and ~4% of pan-tropical GHG
586 emissions. (Le Noë et al., 2021) analyze timber harvest and natural carbon stocks in forests from 1990-
587 2020, using an ecologically-informed dynamic MFA for global forests. They find that if harvest had not
588 increased since 1990, forests could have stored 4.9 Gt of additional carbon. A "no harvest" scenario
589 would have increased biomass carbon stocks by 49.1 Gt, showing substantial mitigation potentials of
590 lower wood use.

591 3.9. State-of-the-art in Agent-Based LEMD modelling

592 ABMs enable detailed representation of (inter)actions of heterogenous agents resulting in emergent
593 non-linear dynamics, hence they can assess distributional aspects, diffusion and uptake of innovations,
594 or shocks and climate damages (Lamperti et al., 2019, 2018) Many studies build on Post-Keynesian
595 theory and evolutionary economics, or derive agent behavior from qualitative research and
596 transdisciplinary co-production. Focusing on agent's decision-making necessitates granular data,
597 which so far results in less emphasis on industrial transformation, as well as data-rich scenarios for
598 material cycles, stocks and energy use. At the national to global levels, ABMs resemble System
599 Dynamics models, as only aggregate agents are considered. For LEMD scenarios, this tradition could
600 be highly useful to model social dynamics and the diffusion of innovations beyond rational optimizers.
601 Given the transdisciplinary, participatory potential to co-develop models and scenarios, this tradition
602 could also be a useful to co-develop locally/regionally grounded LEMD pathways and service
603 provisioning demand together with communities and stakeholders. (Safarzyńska and van den Bergh,
604 2022) study the impact of unemployment and inequalities on the social cost of carbon. (Yazan and
605 Fraccascia, 2020) and (Koide et al., 2023) present concepts for building data-rich scenarios exploring
606 how a more circular industrial system could be implemented at the household and the firm levels,
607 including consumer and supplier decision-making in response to repairing and refurbishing.

608

3.10 Quantitative evidence synthesis of mitigation potentials

The reviewed literature finds substantial potentials for reducing material and energy demand, as well as mitigating GHG emissions (Figure 3). For material use, we find reduction potentials from -1 to -80% when considering all study scopes (Figure 3a). Economy-wide reduction potentials of combined supply- and demand-side measures were reported at 56% when compared to historical base year (i.e. last data-driven year), and 2-47% compared to BAU scenarios (i.e. last year of future scenario). The most effective single measure with a -52% reduction of material footprints compared to 2020 is a scenario of global contraction and convergence to DLS (Vélez-Henao and Pauliuk, 2023). For individual sectors, reductions of up to -63% of phosphorous fertilizer in food systems through a combination of technological and diet change (Springmann et al., 2018) and up to -80% reduction of steel demand through LED-type transformations combining supply and demand-side measures (Oshiro et al., 2021) were reported for annual use in 2050 compared to BAU scenario.

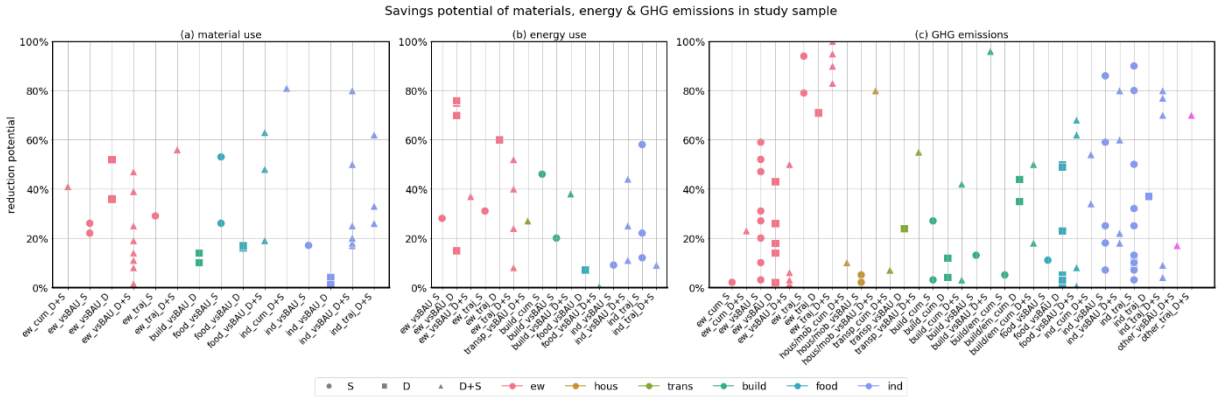

Figure 3: Summary of savings potentials for material and energy use, as well as GHG emissions across all relevant studies, grouped by sectoral and temporal scope, as well as supply-side (S), demand-side (D) and combined supply- and demand-side (D+S) measures. ew = economy-wide, hous/mob= housing & mobility, build = buildings, build/em = buildings embodied flows, food = agriculture & food, ind = industry; cum = cumulative, traj = trajectory from historical base year to scenario year, vsBAU = comparison of annual reduction to business-as-usual scenario). Please note that the exact time and sectoral scopes, as well as mitigation measures within categories might still differ (e.g., some studies accounting cumulative emissions from 2010-30 vs. 2010-50, or industry reduction potentials including estimates for different materials industries like steel, copper, etc.). Due to the comparison to either the historical base year, or a base scenario, values can still be compared. For a detailed account

For energy use, we find reduction potentials of -0.3 to -76%, when considering all study scopes (Figure 3b). The strongest economy-wide reduction potential of up to -76% in 2050 annual global energy demand was reported for demand reductions to DLS (Jarmo S Kikstra et al., 2021), representing a ~60% reduction when compared to historical base years (Millward-Hopkins et al., 2020). These are followed by LED-type transformations combining supply- and demand-side measures with reduction potentials between 40-52% compared to historical base years (Barrett et al., 2022; Gaur et al., 2022; Grubler et al., 2018a). For buildings, we find material substitution to reduce cumulative energy use from 2020-50 in India by -46% (Kumar et al., 2021). For industry, we find global energy use for steel and cement

639 production reduced by -22% and -58% though a carbon tax of 20-100$/tCO2 respectively (van Ruijven
640 et al., 2016).

641 For GHG emissions we find reduction potentials from -1 to -100% when considering all study scopes
642 (Figure 3c). Economy-wide emission reductions between -70% and -100% (i.e. net-zero emissions) are
643 achieved in several studies through combined demand and supply-side measures (Barrett et al., 2022;
644 Costa et al., 2021b; Gaur et al., 2022; Günther et al., 2019; Moallemi et al., 2022). Obviously, the
645 decarbonization of the energy system plays a large role for reducing GHG emissions. Large reductions
646 of economy-wide emissions of individual measures were reported for 3D printing (-27% annual),
647 remote work and active travel (-26%), demand-reduction (-23% cumulative), local/sharing service
648 economy (-18%) and vegan diets (-14%). For additional insights on sectoral potential, please consult
649 the supplemental information section 3.

4. Discussion

4.1. Sector definitions, system boundaries, and modelling principles to depict industrial networks

We identify the below entry points to model the biophysical basis of LEMD scenarios in the reviewed literature, suggesting the need for a unified system definition and shared modelling principles to enable comparability, leverage model combinations, knowledge accumulation and facilitate evidence synthesis.

UNFCC emissions accounting defines the following broad economic sectors: energy supply, industry, agriculture and forestry and other land use (AFOLU), transport, and buildings (Lamb et al., 2021; IPCC, 2022). This “end-of-pipe” perspective on the ‘sources’ of emissions lacks a differentiation of supply and (final) demand and separates interconnected sectors, which jointly respond to demand by forming an industrial network. Depending on statistical practices across countries, extractive industries are variously allocated across energy supply, industry, construction and AFOLU, hindering systematic analysis of material cycles and energy use.

Energy statistics provide detailed information on supply and use of energy carriers for sectors, production processes and final demand, and distinguish between primary, final, and useful energy stages. Leveraging this information is highly relevant for LEMD modelling, to understand potentials and limits of fuel switching, electrification and energy efficiency (Cullen and Allwood, 2010; Sakai et al., 2019).

Raw material extraction and land use, which constitutes the ‘start‘ of material cycles, is reported along boundaries established in the System of Environmental-Economic Accounting (SEEA) and focuses on types of raw materials, e.g., biomass, non-metallic minerals, ores and metals, as well as fossil energy carriers, lacking inherent sector resolution (Krausmann et al., 2017). This data is increasingly used across traditions, requiring modelers to compile data on material cycles and waste by-products occurring at each production step, linkage to input-output tables for sector resolution, as well as differentiation into final products accumulating as stocks (Plank et al. 2022; Streeck et al. 2023a,b). Industry production statistics, such as those for cement or steel, focus on specific stages of the value chain and material cycle, often used eclectically for selective coupling into models.

Waste statistics, if available at all (Tisserant et al., 2017) (United Nations Environment Programme and International Waste Management Association, 2015), cover only what is officially collected and managed in institutionalized waste management systems, leaving large unknowns. Systematic use

requires time-intensive mass-balancing and harmonization to quantify the end-of-life part of material cycles. Some models therefore resort to estimating waste flows as a function of GDP or population, violating thermodynamics i.e. mass-balanced consistency with material extraction, industrial processing, and material stock dynamics.

To model material cycles for LEMD scenarios, we suggest an economy-wide system definition for industry following the SEEA[2] framework which covers extractive sectors and basic industries (agriculture, forestry, mining, refining, processing), manufacturing, construction, energy supply to industries and to final demand, as well as service sectors (transport services, health, financial sectors, etc.), and repair, recycling and waste management sectors. LEMD modelling could be substantially advanced via a consistent depiction of the industrial system regarding physical and monetary layers, supply and demand, interactions between industries, as well as stock vs. flows, at least enabling a clear documentation of any specific model scope to facilitate comparability (Figure 5). Ideally, LEMD scenarios are based on a consistent model of material cycles, from extractive industries to industrial assets and infrastructure to the waste management and circular industries, which is essential for delineating and capturing the implications for energy use and emissions.

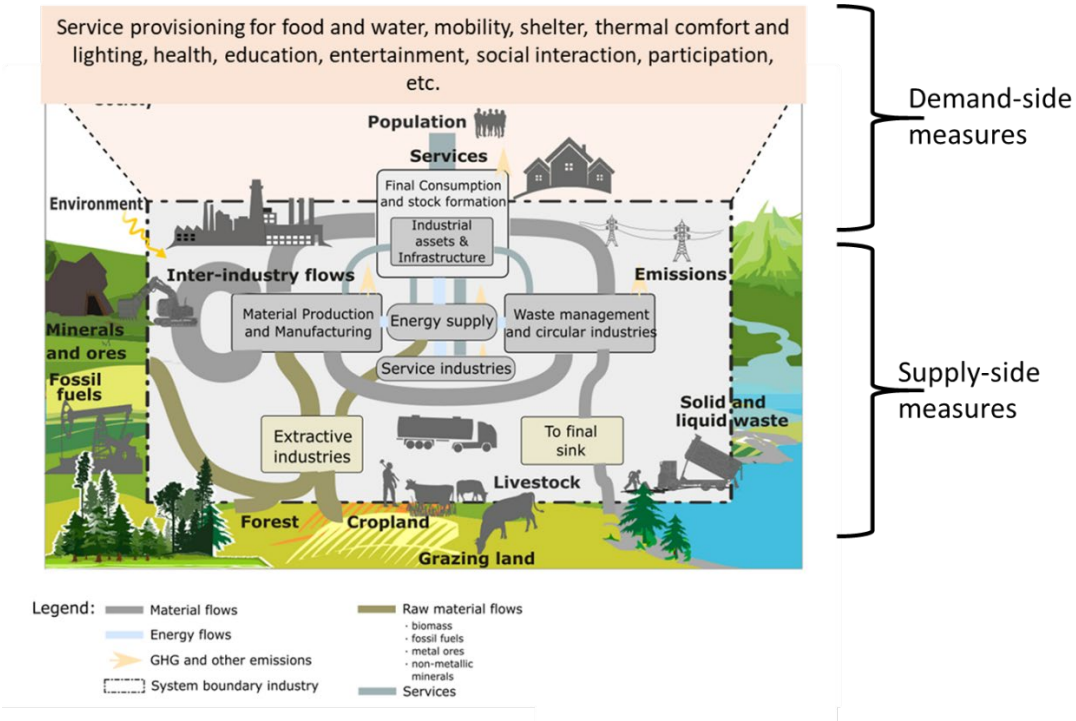

Figure 5: Conceptualizing socio-economic material cycles, energy use, economic sectors and service provisioning, drawing on (Chen and Graedel, 2015; Haberl et al., 2019; Kalt et al., 2019).

[2] The SEEA draws on economy-wide material flow accounting for raw material extraction, energy statistics for sectoral energy use, as well as UNFCC emissions reporting (Krausmann et al., 2017; OECD, 2008) into a (relatively) coherent framework integrating economic, social and environmental information (UN, EU, FAO, IMF, OECD, WB, 2014), however not reporting full material cycles yet.

4.2. Modelling industrial production for LEMD modelling

LEMD modelling of industrial networks needs to depict how supply reacts to changes in demand and service provisioning. At the level of the industrial sector, so-called 'production functions' model the input of labor, capital, energy, and materials in response to intermediate and final demand for each sector's output. A shared understanding and use of appropriate production functions that are consistent across aggregation levels is crucial for LEMD modelling (Keen et al., 2019; Pauliuk et al., 2017; Stern, 2011) (see supplemental information section 6). For a consistent description of material and energy flows and stocks, the mass und energy balance of industrial sectors needs to be respected, which includes a proper accounting of by-products, waste, and emissions. Engineering limits to efficiency need to be respected by the different modelling traditions to prevent the inclusion of unrealistic or even infeasible efficiency gains, including aggregate decoupling of economic growth from energy and materials. Production models should discern different quality grades of energy, such as primary vs. final energy/exergy or high, medium and low temperature heat as well as the different material quality grades required for production. Production functions should allow for varying or incomplete capacity utilization, a common phenomenon in LEMD futures. An option to include more realism in production modelling is to split inputs into fixed inputs that scale with capacity and operating input that scale with the output.

While production functions model individual sectors, models of markets and market mechanisms are needed to determine the market share of different suppliers. A crucial feature of interdisciplinary LEMD industry modelling is to explicitly consider market mechanisms not only for the industrial commodities but also for production factors labor and capital as well as materials and energy carriers. Here, market models from the different disciplines can be combined to accurately reflect the nature of individual markets (equilibrium, disequilibrium, controlled or free).

4.3. Service provisioning and demand modelling

Demand-side LEMD transformation options become visible when making the relations between human wellbeing, service provisioning, product stocks, industry and environmental impacts explicit and assessing decoupling potentials at each step of the so-called Energy Service Cascade[3] (Fig. 5). The reviewed literature predominantly focuses on the demand for shelter, mobility, nutrition and thermal comfort, and less on sectors like health, education and leisure activities (Figure 2). What is actually modelled in most studies are product stocks such as the number of appliances, or weight of buildings (per capita), as well as functions provided by stocks and energy use, such as square meter of well-tempered living space. Service provisioning of 'what is actually demanded' is usually done via exogenously imposed levels of functions, either derived from policy targets, trans-disciplinary deliberations aiming at political legitimacy, or via the researcher's choices.

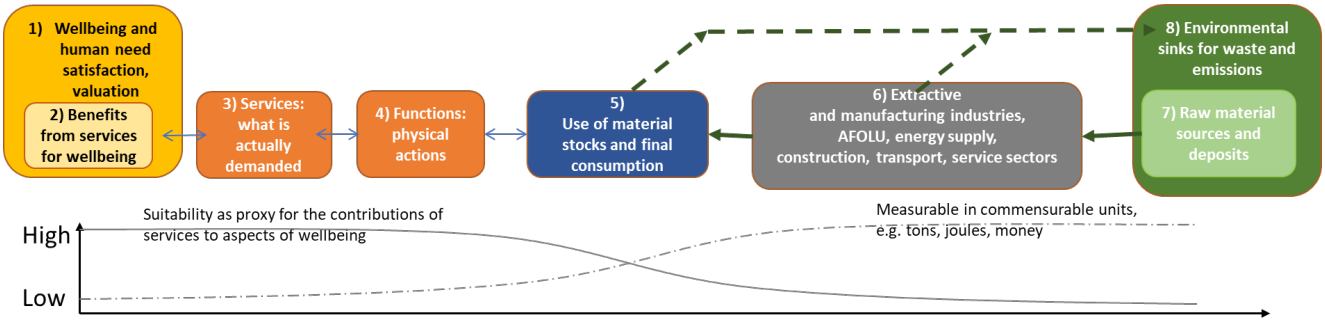

Figure 4: Relations of wellbeing, human needs, to service provisioning, material stocks and economic production, drawing on natural resources, resulting waste and emissions. Adapted from (Kalt et al., 2019).

In the reviewed literature, we find three approaches to modelling demand in general and for service provisioning specifically, via 'consumption functions', which expresses how a basket of goods and services is chosen under constraints. This requires a choice of commensurable units, as well as theoretical assumptions about how actors decide among competing alternatives. First, optimization which is widely used in macro-economic traditions uses variations of (bounded) rational choice theory and monetary valuation, assuming maximization of 'utility' (consumption). Expanding the notion of utility to leisure, unpaid care work, quality of life and wellbeing, as well as non-monetary values seems necessary. Second, exogenously given policy-relevant targets, or extrapolations based on observed economic dynamics are also used, providing useful what-if insights, however often lacking behavioral foundations about who, how and why. Third, policy measures as well as future consumption baskets

[3] As Virág et al. (2022) demonstrate for mobility, more distances travelled don't translate into a better service ('being able to reach places'), or higher wellbeing contributions, and a more explicit representation of the link between human wellbeing, needs satisfaction, the required product functioning and in-use stocks is needed to better understand decoupling potentials on the social side. Such research on low demand scenarios the stock-flow-service-wellbeing nexus is only in its infancy.

749 developed via transdisciplinary co-creation efforts, such as in citizen assemblies or stakeholder
750 workshops, are highly innovative and promising to achieve transformative impacts and insights.

751 4.4. A roadmap for improved LEMD scenario modelling

752 We summarize our insights as eight recommendations for future LEMD modeling to contribute more
753 nuanced, biophysically consistent, and policy-relevant scenarios and insights for climate change
754 mitigation and sustainability. For an extended discussion, see supplemental information section 7.

755 **Interdisciplinary combinations of modelling principles and traditions yield more robust, nuanced and**
756 **policy-relevant insights than any single tradition alone can provide.** Combining models requires
757 carefully considering and potentially harmonizing differences in system definitions and modelling
758 principles (see section 5.1.). Collaborating with the social sciences helps to understand how demand
759 and service provisioning are organized, what acceptable and just low-demand futures could be like,
760 and how they might be achieved.

761 **Thermodynamic and Biophysical Consistency**: To capture economy-wide and time-dependent
762 implications of LEMD scenarios, it's crucial to achieve consistency across material cycles, material
763 stocks, energy use, by-products and waste, and emissions. Ideally, this is achieved at high granularity,
764 spanning from primary extractive sectors, industry and manufacturing, final consumption, recycling,
765 and waste management, to service provisioning. Ideally, economic, biophysical, and social data layers
766 are consistently integrated, complying with their respective rules of consistency.

767 **Stock-Flow-Service Nexus**: The efficiency of transforming material and energy into services hinges on
768 existing material stocks in products, buildings, and infrastructure. Ideally, these relations are
769 consistently represented in models. The SDGs and other policy targets are useful starting points.
770 Transdisciplinary co-creation approaches can be useful to develop context-specific "low-demand"
771 scenarios. Non-monetary service provisioning indicators improve our understanding of the links
772 between wellbeing, human needs, and service provisioning systems.

773 **Wider Spectrum of Supply and Demand-Side Measures**: Enlarging the solution space is necessary to
774 develop net-zero compliant LEMD pathways, which might result in dis-equilibrium, stranded assets,
775 and early decommissioning. This includes standard economic instruments, as well as regulatory
776 measures, product standards, institutional changes, government activities, financial markets, changes
777 in settlement patterns and urban forms, as well as socio-behavioral dynamics.

778 **Assess Telecoupling in Global Supply Chains**: Modeling global supply chain interactions is critical to
779 identify potential rebound effects and burden-shifting, as well as economic winners and losers in LEMD
780 transformations. The different layers of industrial assets (capacity, capital, material stocks), as well as

781 the different stages in supply chains (resource extraction, material production, manufacturing, waste
782 management, recycling, energy supply and service sectors) should therefore be explicitly represented,
783 to understand capital constraints for LEMD scenarios and potential global re-allocations of capital,
784 labour, and natural resources, as well as their transport implications, across global supply chains.

785 **Resource Constraints, Vulnerability, and Resilience**: Modelling should address the complex socio-
786 ecological dynamics, feedbacks, and non-linearities inherent in LEMD transformations and the
787 biosphere. The environment is more than a repository of resources to be extracted and a sink for waste
788 and emissions. Complex trade-offs exist between different environmental aspects, ranging from the
789 climate and biodiversity crisis to other Planetary Boundaries. Some of the reviewed models can
790 address some of these concerns (see supplemental information section XX). Ideally, the social
791 implications of deep structural changes as well as societal crisis for labour, incomes, skills, and
792 inequality are also assessed.

793 **Improved Research Infrastructure, Open Science and Community Standards**: Findable, Accessible,
794 Interoperable, and Reusable (FAiR) research findings and models are crucial for cumulative research
795 and evidence synthesis (Hertwich et al., 2018; Pauliuk, 2020; Wilkinson et al., 2016). Ongoing
796 community efforts, for example by the Integrated Assessment Modeling Consortium[4] (IAMC), the
797 International Transport Energy Modeling (iTEM) network[5], and the Energy Demand changes Induced
798 by Technological and Social innovations (EDITS) network[6] aim to diversify and broaden contributions
799 to the 7th IPCC assessment cycle and beyond. We recommend that LEMD modelers consider the data
800 reporting requirements of such assessments early on in their model development, ideally developing
801 a shared ontology across traditions and models, to facilitate comparability and evidence synthesis.

802 **Connecting to the updated Shared Socioeconomic Pathways (SSPs)** is timely, so that LEMD scenarios
803 can readily contribute to evidence synthesis and global assessments reports. The SSPs are a common
804 framework connecting research on mitigation, adaptation, and impacts. Since their inception in 2014
805 they have been developed further (Green et al., 2022; van Ruijven et al., 2022), with substantial
806 quantitative updates[7] to be released in 2024. More fundamental revisions are also being discussed.
807 Ideally, future LEMD modeling takes up the most recent SSP version and contributes to ongoing
808 discussions about a new low-growth/low-demand SSP. Explicitly quantifying service provision levels in
809 the SSPs is essential for comparability across LEMD models. Additionally, a significant challenge for

[4] https://www.iamconsortium.org
[5] https://transportenergy.org/
[6] https://iiasa.ac.at/projects/edits
[7] https://depts.washington.edu/iconics/, https://www.iamconsortium.org/event/iconics-and-iamc-joint-webinar-shared-socioeconomic-pathways-ssps-update/

new entrants in IPCC scenario submissions is ensuring their models generate sufficiently consistent data for comparison with larger-scale models, while maintaining sectoral or national specificity.

5. Conclusions

We assessed the findings and underlying models of 77 state-of-the-art studies originating from nine modelling traditions published between 2014-2023, which explore Low Energy and Material Demand (LEMD) futures. Interdisciplinary combinations of modelling traditions are on the rise, leveraging their respective strengths for more nuanced and robust insights. We do find large mitigation potentials for materials, energy and GHG emissions across studies, given substantial challenges in extracting, harmonizing, and synthesizing findings. We recommend the development of shared concepts and ontologies, as well as widespread adoption of open science and FaiR data principles, to facilitate comparability as well as systematic and robust evidence synthesis.

We find that service provisioning and demand are increasingly represented via non-monetary indicators for end-use products and the physical actions they provide. An important next step is to assess how much is sufficient for decent living and wellbeing, to develop justified and acceptable scenarios across different contexts. Few models fully link material cycles, material stocks, energy use, waste and emissions in a thermodynamically consistent manner. Those who do are rather coarse in their representation of socio-economic interdependencies and dynamics driving changes. Models with comparatively better representation of socio-economic complexity and dynamics often do not fully comply with thermodynamic principles. In summary, the reviewed models seem to be either too aggregate, or too specific. When considering the multiple properties which are important for modeling industry transformation (detailed physical and economic representation of industrial assets and production flows, detailed representation of the political and legal framework and form behavior given these circumstances, etc.) comprehensiveness at sufficient detail is a criterion hardly achieved.

To improve LEMD modelling, we herein propose a general comprehensive system definition and eight suggestions for future work. A question for further exploration is how the required comprehensiveness and granularity can be achieved in a resource-efficient way, so that real life decisions can be robustly informed.

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SI-1) Research design, criteria of relevance and methods

This review was developed by the authors through intensive interdisciplinary collaboration across modelling traditions and methodological approaches (Figure 1).

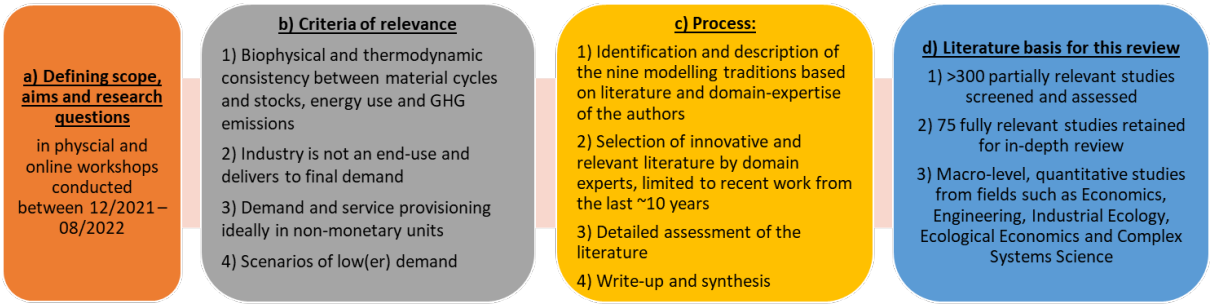


Figure 1: Overview for the review process, design and workflow.

We collected state-of-the-art modelling studies from each tradition complying with the criteria of relevance, interpreted generously (Table 1). Literature was selected via the domain expert's knowledge of their fields. Literature collection was conducted between 03/2022-09/2023, for which we screened scientific literature databases, conducted citation snowballing, and selected literature based on our expertise and judgement; not aiming for comprehensive 'systematic' coverage, but rather selected highlights and recent i.e. state-of-the-art work. A common review framework was used to assess the literature, to derive the respective sections about each tradition, and to develop the concluding discussions (see supplementary information for details).

Table 1: Criteria for inclusion/exclusion of peer-reviewed research articles.

1.	Does the study jointly model materials, energy (and GHGs) with an empirical basis in physical units?
2.	Does the study use social and/or physical indicators on demand, services, wellbeing & social progress, i.e., non-monetary indicators for material and energy services?
3.	Does the study cover industry as intermediate user/supplier and does it contain modelling of industrial production, e.g., intermediate (upstream/downstream) inputs and/or outputs from industry for a certain service/final demand?
4.	Does the study model demand-side changes for industry output, e.g., is demand seen as variable and/or is used as scenario variable (instead of being a non-questionable given): E.g., explorations of low demand, low growth, post-growth, stabilization, degrowth, reductions of demand and consumption?

Each study was then assessed in detail, along a common review framework (see supplementary data file). Based on this information and through careful study of each article, the lead author prepared a discussion paragraph for each study (see below here). From this material, a condensed summary was then prepared for the main manuscript.

Granularity and resolution of industry/economic sectors

Across all studies and traditions, the terms “sector” or “industries” are not used in a harmonized nor necessarily well-defined manner. For this review, our aim was to assess the granularity of the utilized model, especially regarding the number of economic sectors and their interactions (primary, secondary, tertiary). Most studies are based on input-output tables, which directly gives a count of “sectors”. For other modelling traditions, the respective study and its supplementary information and/or model documentation was consulted, to determine the exact number of economic sectors in the model.

To consistently account for industry/economic sector granularity (especially for modelling traditions that did not use input-output tables as underlying industry structure), we counted either by multiplying general processes (e.g. production, fabrication) by the number of materials (when material cycles are explicitly modelled like in MEFA), or by adding the material count to final demand sectors (when material cycles are not explicitly modelled). In input-output tables, each material production industry depicts one sector. For system dynamics models, a modelling tradition where the term “sector” is interpreted more broadly, we took a closer look at the sector list to identify which ones represent economic sectors in the sense of the System of National Accounts.

Granularity and resolution of service provisioning modelling:

The Energy Service Cascade was proposed by (Kalt et al., 2019) and yields the conceptual/analytical distinction of biophysical structures, functions, services, and their valuation. For all details, we refer to the respective publication. Herein, we utilize and adapt this conceptual framework and assess, how studies model the biophysical structures of the economy, which functions they assess and how, insofar ‘service provisioning’ is modelled, and which indicators are used to express societal well-being.

In order to display our results in graphics, we harmonized within-category indicators to some degree which might slightly deviate from originally reported categories for some studies. The counts are reported before the harmonization process where some categories were summed up (e.g., heating, cooling --> heating/cooling). Products were counted when modelled in product units, mass of material cycles, or expenditures in input-output tables. Some of the products listed here might in practice have an activity focus (e.g., when stemming from input-output tables, the residential buildings sector might also include roads (see e.g., (Streeck et al., 2023b, 2023a)); this is neglected here). Differences in energy and energy carriers were not accounted for.

Table 1: Frequency of product groups in the set of fully-relevant studies.

Product group	Count	Product group (cont.)	Count (cont.)
appliances	15	civil_engineering	3
food	15	packaging	3
machinery	14	generic_product	2
motor_vehicles	13	agriculture	2
construction	12	other_goods_services	1
residential_buildings	11	consumer_goods	1
service_sectors	7	containers_other	1
electronics	7	water_sector	1
textiles	7	wastewater_sector	1
other_transport	6	harbors_airports	1
electrical	6	railways_telecom	1
nonresidential_buildings	5	parks	1
transport	5	waste_treatment	1
clothing	4	shipping_container	1
total_material_stock	4	consumer_products	1
buildings	4	forest_products	1
furniture_other	4	cooking_stoves	1
roads	4	services	1
cars	3	infrastructure	1

Table 2: Frequency of function indicators in the set of fully-relevant studies.

Function	Count	Function (cont.)	Count (cont.)
housing	24	waste_mgmt	2
passenger_transport	20	meat_in_diet	2
nutrition	15	health_expenditure	2
heating	13	education_expenditure	2
cooling	13	sanitation	2
nonresidential_floorspace	11	washing_facilities	1
freight_transport	10	building_floorspace	1
water_use	5	data_volume	1
illumination	4		
water_heating	2		

Table 3: Frequency of service indicators in the set of fully-relevant studies.

Service	Count	Service (cont.)	Count (cont.)
employment	9	energy_access	1
dls	6	affordable_energy	1

thermal_comfort	4	sanitation_access	1
healthy_diet	2	water_access	1
car_safety	1	wood_supply	1
time_saving	1	road_access	1
affordable_housing	1		

Table 4: Frequency of welfare & co-benefit indicators in the set of fully-relevant studies.

Welfare & co-benefits	**Count**	**Welfare & co-benefits (cont.)**	**Count (cont.)**
gdp	17	hdi	1
land_footprint	4	education_levels	1
value_added	3	npv	1
inequality	3	social_cost_of_carbon	1
air_pollution	3	c_sequestration	1
biodiversity_conservation	2	acidification	1
premature_deaths	2	eutrophication	1
material_criticality	2	ecotoxicity	1
food_waste_reduction	1	human_toxicity	1
climate_damage	1	governance	1
energy_security	1		
sdg	1		
life_expectancy	1		

Methodological documentation on the quantitative evidence summary

To quantitatively synthesize evidence on reduction potentials for energy and material use and GHG emissions, we either directly extracted reduction potentials relative to the base year (i.e. last-data driven year) or business as ususal (BAU) scenario, or tried to calculate relative reduction potentials if numbers were not directly accessible but sufficient information was provided in the maunscript or the annex. We distinguished between different mitigation scopes, timeframes and mitigation measures. For scope, we grouped the studies under the following categories: Economy-wide, buildings (direct or only embodied resource use), housing & mobility, transport, food and industry. Depending on the timeframe of the studies and on the information that was accessible to us, we identified relative reduction potentials by either (1) relating the absolute reduction potential to the historical base year (e.g. 2020), (2) the annual absolute reduction potential in the 'mitigation scenario' versus a baseline BAU scenario (e.g. 2050), or (3) the cumulative reduction potential over the prospective period in the 'mitigation scenario' versus cumulative resource use in a baseline BAU scenario (e.g. 2020-2050). Mitigation measures were taken from the literatures and grouped under the categories of supply-, demand and combined supply-demand side measures. Due to the multitude of different combinations of mitigation scopes, timeframes and combinations of measures, a fully harmonized synthesis could not be obtained. Instead, the information provided in section 4.10 in the main manuscript provides an overview over documented mitigation potentials by combinations of mitigation scope, timeframe and supply vs. demand-side measures. For granular depiction of the mitigation potential reported in studies, please consult the supplemental data file.

Coverage of mitigation measures

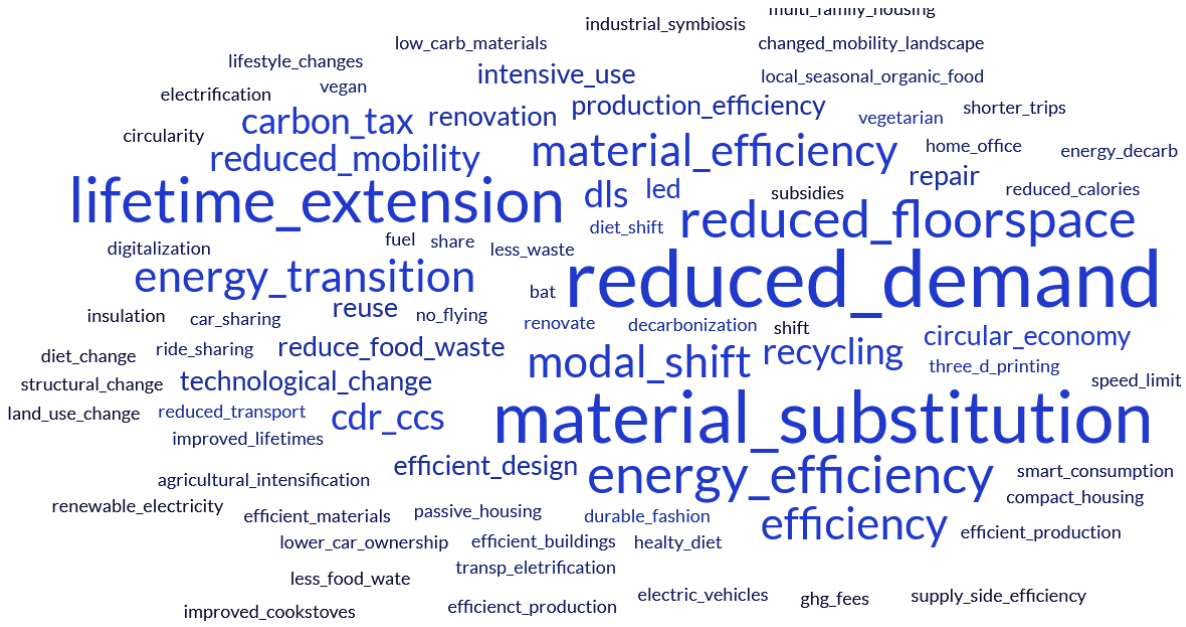


Figure 2: Overview of supply- and demand-side measures covered over 75 relevant studies with indication of frequency according to size.

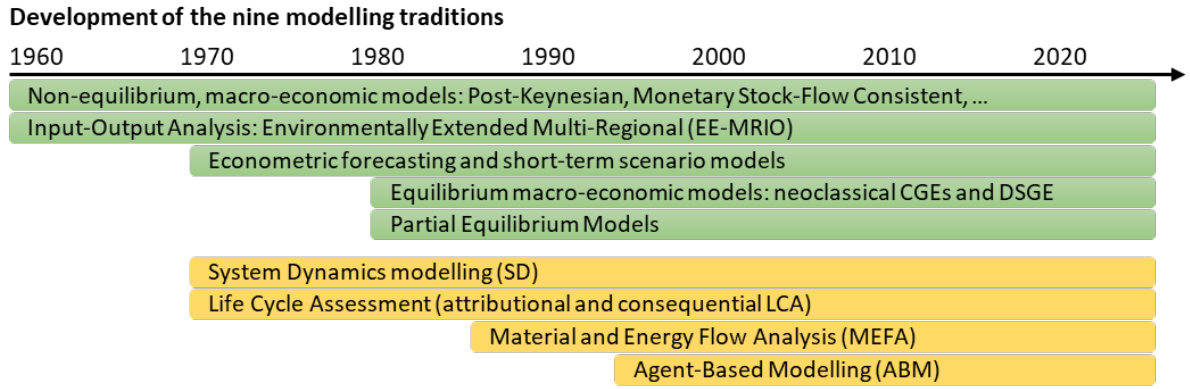
Table 5: Documentation of frequency of supply- and demand side measures in 75 relevent studies for Figure 2.

Measure	Count	Measure (cont.)	Count (cont.)
8	reduced_demand	1	healty_diet
7	material_substitution	1	car_sharing
6	lifetime_extension	1	ride_sharing
5	reduced_floorspace	1	bat
5	energy_efficiency	1	efficient_buildings
4	modal_shift	1	transp_eletrification
4	material_efficiency	1	improved_lifetimes
4	energy_transition	1	energy_decarb
4	efficiency	1	low_carb_materials
3	reduced_mobility	1	efficient_production
3	cdr_ccs	1	smart_consumption
3	recycling	1	electric_vehicles
3	carbon_tax	1	agricultural_intensification
3	dls	1	compact_housing
2	circular_economy	1	efficient_materials
2	led	1	shorter_trips
2	repair	1	speed_limit

2	reuse	1	efficienct_production
2	reduce_food_waste	1	digitalization
2	production_efficiency	1	lower_car_ownership
2	efficient_design	1	changed_mobility_landscape
2	intensive_use	1	lifestyle_changes
2	renovation	1	fuel
2	technological_change	1	shift
1	reduced_transport	1	multi_family_housing
1	decarbonization	1	electrification
1	three_d_printing	1	insulation
1	durable_fashion	1	ghg_fees
1	renovate	1	circularity
1	diet_shift	1	subsidies
1	vegetarian	1	supply_side_efficiency
1	vegan	1	diet_change
1	local_seasonal_organic_food	1	less_food_wate
1	less_waste	1	improved_cookstoves
1	share	1	structural_change
1	no_flying	1	land_use_change
1	home_office	1	industrial_symbiosis
1	passive_housing	1	renewable_electricity
1	reduced_calories		

SI-2) Introduction and overview for the nine modelling traditions

The reviewed modelling traditions have been developed over the last ~60 years (Figure xx). Especially the macro-economic traditions build upon longer standing conceptual and empirical developments in (macro)economics. The biophysically oriented traditions usually have a shorter intellectual history to build upon (green).



The **non-equilibrium macro-economic tradition** draws on Schumpeter, Keynes, Kalecki and Kaldor, emphasizing non-linear structural change and supply-demand imbalances (Lavoie, 2022; Mercure et al., 2019). Conversely to neo-classical equilibrium approaches, it models demand-led economic growth with potential under-utilization of factors of production (e.g., unemployment). This tradition explicitly includes money and finance and distinguishes between consumption and investment. Model parameters are calibrated with econometric methods applied to historical time series. Typical assumptions are demand-determined equilibrium without full utilization of resources (capital goods and labor), bounded rationality and uncertainty (the actors make decisions based on expectations from forecasts or historical information, e.g., lagged income as a proxy of the expected one (Dafermos et al., 2017), non-optimal but reasonable decisions (e.g., based on heuristics rules), dynamic adjusting process (vis-a-vis a perceived disequilibrium), prices as indicators of reproduction costs rather than scarcity, and outcomes driven by historical events and path dependency (more details in Lavoie, 2022). Depending on the production- and consumption functions and the granularity of the utilized data, biophysical and thermodynamic consistency is often violated (Keen et al., 2019; Pauliuk et al., 2017; Stern, 2011). Modern applications are built on (Godley and Lavoie, 2012) and usually are monetary stock-flow consistent (SFC) Ecological Macro-Economic models (Cahen-Fourot and Lavoie, 2016; Fontana and Sawyer, 2016; Hardt and O'Neill, 2017).

Environmentally Extended Input-Output Analysis (EE-IOA) treats materials and energy as inputs, and waste and emissions as outputs of the economy, using a linear, static Leontief production function to model interactions between economic sectors/industries and final demand (Leontief, 1970). IOA was

developed alongside the System of National Accounts, yielding Input-Output Tables as key data source for many modelling traditions. Modern applications include deriving consumption-based resource and emissions 'footprints', and modelling scenarios of structural and lifestyle changes. IO-based scenario assessments exogenously adapt different elements of the static IO model, e.g., emission intensities, input-mix of industries, trade-linkages, and demand patterns (Hoekstra and Wiedmann, 2014; Wiedmann and Lenzen, 2018).

Macro-econometric forecasting uses econometric equations to empirically infer human behavior from historical data, including past responses to economic stimuli, such as changes in prices.[1] This tradition is consistent with post-Keynesian macroeconomic thinking, and relies on very few assumptions regarding agents and firms' behavior -- i.e., agents are not rational, do not have perfect information, nor do they optimize. Path dependency is a key feature of macro-econometric modelling simulations: while few behavioral assumptions are imposed, behavioral responses are assumed constant over time (European Commission 2017, Cambridge Econometrics 2022). For this reason, these tools are best suited for short to medium term forecasting (Jebaraj and Iniyan, 2006). To overcome this limitation, macro-econometric models can be complemented with other modeling approaches to capture disruptive changes, as is the case for the E3ME model for what regards the modelling energy demand and investment (Cambridge Econometrics 2022).

The **equilibrium-based macro-economic tradition** draws on Walras and encompasses widely used Computable General Equilibrium (CGE) and Dynamic Stochastic Equilibrium Models, grounded in neoclassical economic theory. Their core assumption is efficient price coordination among agents, making 'rational' optimal decisions on commodity demand and production factor allocation, given labor and resource constraints. In CGE models, representative rational agents allocate factors to maximize profit/utility/consumption, driving economic growth and structural change (Figure 3b). This determines production volumes and commodity prices, ensuring supply equals demand across markets. Depending on the production- and consumption functions and the granularity of the utilized data, biophysical and thermodynamic consistency are usually violated, similar as in the non-equilibrium tradition (Keen, 2021; Keen et al., 2019; Pauliuk et al., 2017; Stern, 2011). IAMs from this tradition include AIMS-CGE or GEM-E3, which are widely used for climate mitigation scenarios.

[1] Econometric methods use historical data to identify statistically significant relationships between variables, which can be used to inform many models. Econometrics, for example, can be used to estimate parameters of specific functions (e.g., price elasticities, elasticities of substitution between inputs, etc.) to be used in several models, including general equilibrium models and optimization models. Conversely, macro-econometric models rely on econometrically specified relationship between variables and project them forward.

Macro-economic partial-equilibrium (PE) models seek an 'optimal' solution for supply-demand in specific commodity markets, using detailed engineering descriptions of technologies and industrial processes, treating the rest of the economy as exogenous (Figure 3b). They use exogenous drivers such as GDP or demand for material, energy, and energy services and represent natural resources and production capacities with supply-cost curves, predefined potentials like maximum wind energy capacity, and external prices such as import prices for hydrogen or biomass. The International Energy Agency's MARKAL (MARKet ALlocation) model was introduced in the 1970s and the TIMES model in the 2000's, which are widely used nowadays. In 1998, MARKAL-MATTER was developed to incorporate material aspects of GHG reduction strategies. PE models are extensively used to model energy transition scenarios, e.g., in IAMs such as MESSAGEix and IMAGE.

System Dynamics (SD) simulates the non-linear evolution of complex systems over time, based on interactions among their components, explicitly biophysical stocks and flows over time (Radzicki and Taylor, 2008) (Figure 3b). Early applications focused on the industry sector, and notably the World3 model for the Club of Rome's 'Limits to Growth' reports (Meadows and Club of Rome., 1972). Industrial SD applications often address supply chain dynamics, disruptions, and actor behavior, with fewer focusing on long-term system evolution. Recent examples in the environmental context include the iSDG model (Allen et al., 2019), or the IAM PE model IMAGE (van Ruijven et al., 2016), and the GCAM model (https://jgcri.github.io/gcam-doc/demand_energy.html),

Life Cycle Assessment (LCA) was developed to inform product choices and improvement options, starting from detailed physical production descriptions, then modelling all required materials and energy from "the cradle to the grave", in a bottom-up manner (Curran, 2013; Finnveden et al., 2009; Heijungs and Suh, 2002) (Figure 3). LCA typically compares products or processes via normalization to "functional units", like m² of floor area or km of mobility and uses study-specific system definitions, usually focusing on small consumption units and marginal changes. Several LCA databases and software packages have been developed to facilitate application. LCA is increasingly combined with other traditions, including EE-IOA to address widespread truncation errors of global supply chains (Suh et al., 2004), endogenously represent industrial production structure, and market mixes based on representative data. Two approaches are increasingly differentiated: attributional LCA describes existing, static life cycles and products, while consequential LCA aims to also simulate feedbacks and economy-wide repercussions of large-scale changes. LCAs in general and especially these two approaches can yield very different results, depending on system boundaries, allocation choices, functional units, inclusion/exclusion of feedbacks and underlying databases used (Hellweg et al., 2023; Hertwich et al., 2018).

Material and Energy Flow Analysis including dynamic stock-flow modelling (MEFA), is widely used in resource- and waste management (Graedel, 2019), as well as to quantify economy-wide resource use along system boundaries of the System of National Accounts, used as indicators nationally and in the SDGs (Eisenmenger et al., 2020; Krausmann et al., 2017) (Figure 3). MEFA is based on the concept of social metabolism, conceptualizing society as socio-ecological 'organisms', requiring inputs of material and energy to sustain their biophysical stocks of people, livestock and material stocks, thereby producing waste and emissions (Fischer-Kowalski, 1998; Gerber and Scheidel, 2018). MEFA is grounded in the Laws of Thermodynamics, which entails biophysical consistency across all physical inputs, stocks, and outputs. In recent years, dynamic MEFA is increasingly used to simulate stock/demand- or inflow/supply-driven scenarios, assessing technical/physical potentials and limits of material efficiency and circular economy strategies, e.g., lifetime extension, lightweighting, reuse, recycling, downsizing (Hertwich et al., 2019; Worrell et al., 2016).

Agent-based models (ABMs) simulate the actions and interactions of autonomous agents within specific environments, modelling non-linear, complex, emergent phenomena (An et al., 2021) (Figure 3a,b). Based on van Neumann's Cellular Automata and Schelling's model of segregation, ABMs can model supply chains, industrial or land use systems based on agents' behavior and decision-making. ABMs are versatile and can address spatial interactions and feedbacks, heterogeneity, learning, and stochasticity. ABMs are increasingly used to improve Integrated Assessment Models (Caiani et al., 2016; Lamperti et al., 2019). ABMs apply two key principles (Heckbert et al., 2010): (1) dynamic behavior of agents and their interactions yields emerging system properties, (2) agent interactions consider both space and time. ABMs dynamically formalize behavior, moving beyond conventional assumptions like 'homo oeconomicus' (Schlüter et al., 2017). They can integrate qualitative data and mixed methods. ABMs can be based on empirical or theoretical data (Huber et al., 2018).

SI-3) Additional results

Studies for the Global North vs. South and FAiR principles by modelling tradition

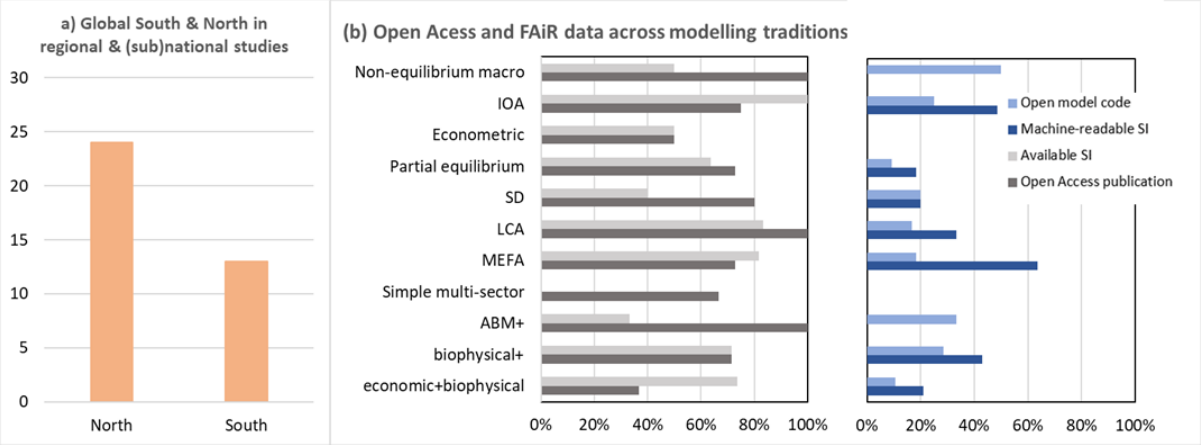


Figure SI-3: Amount of studies covering the Global South vs. North in regional and (sub)national cases across fully-relevant studies, as well as FAiR principles by modelling tradition.

Modelling the environment, feedbacks and limits for LEMD scenarios

Regarding ecological and resource limits and feedbacks, as well as other environmental concerns, we find that studies across the macro-economic traditions usually represent some forms of ecological, technical and social feedbacks and limits, although with different empirical basis, mechanisms and operationalization (Figure 5a). Such limits and feedbacks include damages and disruptions from climate change, raw material shortages, lack of skilled labour, technological diffusion speeds, as well as scale and speed of societal change, indicating an important future research frontier for future model developments. Regarding other environmental concerns than GHG emissions, we find that about half of the reviewed studies include other environmental pressures and impacts in their modelling, for example land use, air pollution, and eco-toxicity (Figure 5b). This shows the potentials to address a larger set of environmental and social sustainability considerations, for example also regarding biodiversity and air quality impacts.

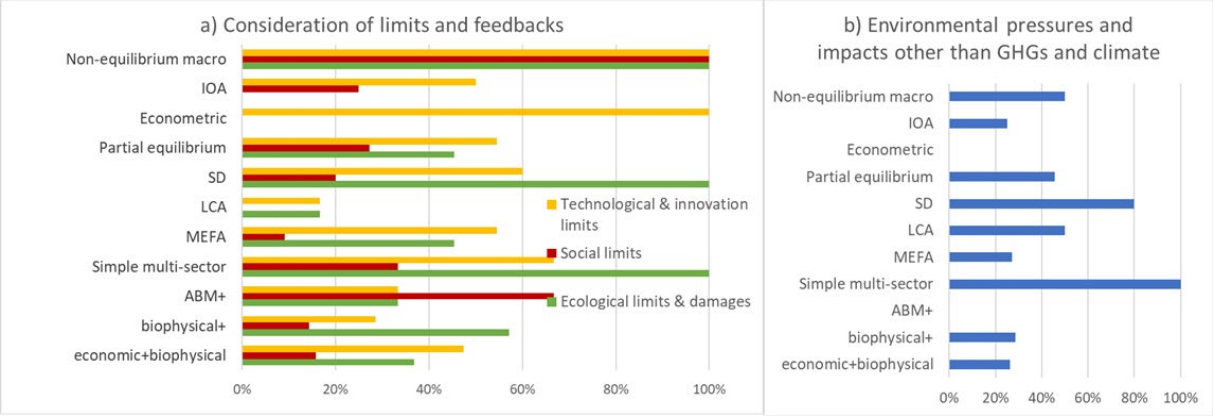


Figure 4: Modelling of limits and feedbacks across the studies from each tradition. Please note, that we did not conduct a detailed assessment of which ones and how exactly those limits and feedbacks were modelled, rather aiming for a general overview if studies attempt to.

SI-4) Detailed discussion of the state-of-the-art by tradition

SoA in non-equilibrium LEMD modelling

Stock-flow consistent (SFC) Ecological Macro-Economics has so mainly dealt with energy and GHG emissions (D'Alessandro et al. 2020; Jackson & Victor 2020; Jacques et al. 2023; Nieto et al. 2020a,b). Extending their model scopes to material cycles has begun for global transport and the transition to electric vehicles (Pulido-Sánchez et al., 2022) and in a global IAM (Capellán-Pérez et al., 2020).

(Dafermos et al., 2017) apply the post-Keynesian, Stock-Flow-Consistent (SFC) approach with Georgescu-Roegen's flow fund model to the global economy. Highly innovatively, this model explicitly formalizes monetary and physical stocks and flows, complying with financial accounting rules and the Laws of Thermodynamics. They distinguish stocks-flows and funds-services, drawing on (Georgescu-Roegen, 1971), who introduced the latter as the capability of a stock-flow combination to provide services. Production and material use is demand-driven, with supply constraints due to environmental damages and energy/material constraints. Climate change directly affects components of aggregate demand. Finance impacts macroeconomic activity and investment, influencing resource efficiencies. The model encompasses material extraction, recycling, energy use, and GHG emissions in a stylized semi-empirical manner, used in exploratory scenarios.

Similarly, (King, 2020) present a stylized model building on post-Keynesian theory with monetary and biophysical stock-flow consistency (SFC), implemented in System Dynamics using Input-Output Tables. The model considers a finite, regenerating natural resource and energy availability, which indirectly constrains output due to its essential role for capital operation and sustaining the population, as well as labor availability constraints. It distinguishes between capital for resource extraction and goods

production. Based on granular, data-rich empirical implementation, inclusion of physical service indicators and heterogenous demand representations, as well as revisiting constraint assumptions, both models could provide highly insightful LEMD scenarios.

SoA in Environmentally-Extended Input-Output Analysis for LEMD modelling

(Vita et al., 2019) assesses GHG impacts of a widespread adoption of sufficiency and green consumption, using the EXIOBASE MRIO. They translate 41 specific measures derived from stakeholder workshops into changes in final demand and industrial structure in the MRIO. A flow-consistent physical layer for food and energy is used, while the rest of the economy is represented in monetary units. They find that a local, sharing-based service economy can reduce Europe's carbon footprint by up to -18%, with sharing and extending the lifespan of clothing and appliances contributing -3%. Reducing motorized transport through remote work and active travel could result in -9% to -26% reductions, while vegan diets could result in a -14% reduction. Potential rebound effects are considered as uncertainties. This study innovatively links stakeholder driven LEMD visions to macro-level modeling. For LEMD scenarios, material stocks and material cycles, endogenous feedbacks, and a broader range of physical service indicators beyond food calories and energy need to be included.

(Wiebe et al., 2019) employ the MRIO model EXIOBASE v3[1], to model global effects of circular economy measures on material cycles and employment. They use economy-wide physical data from the System of Environmental-Economic Accounting on material and energy extraction, and waste. Their material cycles are mass balanced for reported material flows, however excluding material stocks and suffering from considerable data quality issues in reported waste statistics (Tisserant et al., 2017). They differentiate primary and secondary industries, using detailed life-cycle data. They find that until 2030 and compared to a growth BAU scenario based on the IEA's ETP 6° scenario, the modelled measures could result in a -27% decrease in metal extraction, an -8% reduction in fossil fuel extraction, an -8% decline in forestry products, and a -7% decrease in non-metallic minerals. For LEMD modelling, explicitly modelling material stock dynamics would improve waste and recycling estimates, endogenizing feedbacks and structural changes, and integrating physical service indicators.

(Wenz et al., 2020) simulate GHG emissions and economic costs for providing universal access to 'all-season' road infrastructure globally (SDG 9.1). They map existing road infrastructure and population patterns and estimate the additionally required asphalt roads, as well as the potentially induced car traffic via elasticities. Based on typical construction costs, country-specific emission intensities and global supply chains from the GTAP MRIO, they model direct and indirect GHG emissions, assuming

static emissions intensities. Providing road access to >97.5% of any country's population would result in 2 Gt CO2 emissions for construction, and 200 Mt CO2 annually due to induced traffic, if all roads were constructed by 2030. Material cycles and stocks, as well as energy use in industry for construction and the production and use of vehicles are only indirectly represented via monetary relations across broad GTAP sectors. This study usefully demonstrates how to address internationally agreed upon targets for access and service provision vis a vis existing under-provision, showing that even with static emissions intensities, providing universal access would result in low GHG emissions. For LEMD scenarios, dynamic and consequential modelling of decarbonizing energy systems and supply chains, full material cycles and stock accumulation, as well as different transport modes and spatial configurations of road networks could produce novel insights for addressing critical under-provisioning with less resources and emissions.

(Donati et al., 2020) introduce a scenario framework and open software package to model product lifetime extension and resource efficiency using the MRIO EXIOBASE v3. They implement measures in the buildings and transportation sectors, as well as affected upstream sectors by modifying final demand and industrial production in the linear Leontief model. They find potential reductions of -10% for GHG emissions, -13% for raw material extraction, -4% for land use, and -15% for blue water withdrawal, as well as -6% in Value Added and -5% in employment. Future steps should include explicit consideration of material stock dynamics, physical service indicators, and endogenous dynamics.

(Garvey et al., 2021) employ a hybrid monetary-physical input-output version of the UK MRIO to model a transition to alternative diets in the UK, considering trade impacts with 14 world regions. Their scenarios encompass food waste reduction, recommended calorie intake, and dietary transition, applied individually and in a combined scenario. The most ambitious scenario results in a remarkable -52% reduction in territorial GHG emissions by 2050, with dietary transitions contributing significantly with reductions ranging from 22% to 44%. This approach also effectively addresses the UK's consumption-based food emissions, which are 52% higher than current territorial emissions within the UK.

(Hayashi et al., 2022) study the potential of ICTs to mitigate food waste and GHG emissions in Japan, using an IO model. They focus on direct online food sales, advanced production predictions using weather forecasts, order management to prevent over-cooking, and household food wastage monitoring apps. They employ an intermediately resolved national IOT for Japan, covering 56 sectors, as well as 13 different food-production related materials. Trade is ignored. Counter-factual scenarios are analyzed by modifying final demand and industrial structures, without considering price fluctuations or rebound effects. They find a hypothetical 50% reduction in food waste, facilitated by

increased ICT equipment production could potentially reduce Japan's total energy consumption and GHG emissions by -0.2% to -0.4% of primary energy supply and -0.4% to -0.6% of GHG emissions compared to 2011 levels. For LEMD modelling this study shows how to implement ICT-based innovations into simple counter-factual scenarios and how they might affect industrial production.

(Gast et al., 2022) quantify global technical potentials for industrial GHG mitigation through supply-side industrial symbiosis across bulk material industries and energy use for the year 2017. They quantify global material cycles and energy use from raw materials extraction to industrial production recipes and technologies, holding demand constant. They merge MFA and hybrid multiregional input–output analysis (MRIO). While previous industrial symbiosis studies operated at plant/industry/regional levels, this is the first global assessment for steel, cement, paper, and aluminum. They find that even major changes to byproduct utilization in cement production result in low GHG mitigation potentials, at -7% of the total bulk material system emissions. New technologies for heat recovery could enable larger emissions reductions of up to -18%, however the necessary infrastructure and technologies are not yet deployed at scale. If industrial symbiosis is to be promoted, the top priorities are intensified utilization of other cementitious materials and flue gas heat recuperation for electricity generation and heat exchange. Importantly, the authors caution against over-reliance on existing byproduct utilization, which could lead to entrenched high-carbon infrastructure and dependencies on current industries and production levels. This study provides an innovative approach for conducting technology-rich and thermodynamically consistent assessments of industrial production, material cycles, byproducts, and energy use at the macro-level. For scenarios related to Low-Emission Material and Energy Demand (LEMD), expanding the scope to include material stock dynamics for secondary end-of-life materials and assessing demand-side measures from a service provisioning perspective would be highly beneficial.

SoA in econometric modelling and forecasting

(Pollitt et al. 2020) employ the E3ME model, a data-rich non-equilibrium, econometrics-based IAM, to assess the impact of materials taxation for the carbon-intensive sectors basic metals (steel, aluminum) and cement. They draw on material use rates from MFA (Pauliuk et al. 2016) to estimate sector unit costs and modify input-output coefficients; they also incorporate exogenous assumptions about energy intensity. They find that a €80/tCO2 materials tax could reduce the EU's energy-related emissions by 6% and process emissions by up to 40%, without carbon leakage, with minimal GDP impacts and slight employment reductions.

Econometric modelling is also employed alongside other modelling traditions. For instance, (van Ruijven et al. 2016) 2016 rely on carefully selected regression models to build a relatively detailed bottom–up steel and cement model embedded in a long-term global energy system model. They use this model to generate future projections or steel and cement demand based on the SSP2 scenario. While demand is shown to increase rapidly in absence of climate policies, they show considerable potential for emission reductions from steel and cement industries, leading to resp. 80–90% and 40–80% reduction below 2010 in 2050 for a carbon tax of 100 $/t$CO_2$ + 4%pa. Yet, their reuslts are highly sensitive to the availability of CCS.

(de Souza and Pacca, 2021) evaluate the potential of recycling and charcoal as measures for the production of low carbon steel in Brazil: to this end, they use an econometric model to forecast Brazilian steel production up to 2050 and combined this information with estimates of the technical amount of scrap and the economic feasibility of charcoal. They show that combining these two strategies could significantly reduce emissions associated with steel production: a recycling share of 36% of the total steel production could reduce these emissions by 20%. Furthermore, 86% of the remaining blast furnace production could to be based on charcoal, improving the total abatement by 65%. Of these two options, charcoal presents higher abatement costs but less uncertainty than recycling. Extending on this analysis, (de Souza and Pacca, 2023) evaluate the potential CO2 mitigation associated with the implementation of circular economy (CE) strategies considering both the cement and steel industries in Brazil. CE strategies considered are: recycled-based EAF and charcoal-fired BF – as opposed the traditional coal-fired BF – in the cement industry; material efficiency, the substitution of supplementary cementitious materials (SCM) for clinker in both cement production and use stage and the substitution of petroleum coke with alternative fuels. Their results show that the application of CE approaches in different sectors through the lens of industrial symbiosis increase the opportunities for economic savings and carbon reduction. Specifically, sustainable charcoal-based steelmaking as the greatest CE emissions abatement measure; industrial symbiosis reduced the average abatement cost, but does not result in significantly lower emissions. Together, circular practices and industrial symbiosis can avoid 52% of the business-as-usual emissions up to 2050 at US$ 10/tCO2e.

A highly innovative and notable effort not yet addressing material cycles explicitly is the MARCO-UK model, which is a macro-econometric model based on post-Keynesian economic theory, where agent behaviour is not based on optimisation but is instead determined from econometric equations based on historical data, using over 150 socio-technical-economic variables, including thermodynamic-based energy variables (primary energy, final energy, and useful exergy; thermodynamic efficiency at

primary-to-final and final-to-useful conversion stages). MARCO-UK is the first energy-economy-wide model to include thermodynamic (energy) efficiency, and the useful stage of energy consumption (as useful exergy). The inclusion of thermodynamic efficiency and useful exergy allows us to investigate their roles in economic growth - for example (Sakai et al., 2019) found that around a quarter of historical UK economic growth since 1970 could be attributed to gains in economy-wide thermodynamic energy efficiency. The model can also be used for study of the socioeconomic impacts of energy transition topics - such as a rapid country-wide building retrofit in the UK (Nieto et al., 2020) and the electric vehicle transition (Nieto et al.).

SoA in equilibrium-based macro-economic LEMD modelling

The (OECD, 2019) 'Global Materials Outlook' is based on an advanced and granular macro-economic equilibrium CGE model, extended with economy-wide raw material extraction data as well as energy use, waste and secondary materials, GHG emissions and multiple other environmental and social impacts, using input-output tables embedded into a Social Accounting Matrix. The CGE model is built upon the GTAP MRIO, disaggregated to differentiate primary and secondary materials processing using the high-resolution MRIO EXIOBASE. They endogenously model economic growth based on the Solow growth model extended by human capital which violates thermodynamics, and assume global convergence of income and automatic energy efficiency improvements. Industrial capital vintage turnover constrains substitution in the short-term, while assuming perfect substitution in the long-term. In their baseline scenario, global material extraction of metallic ores, non-metallic minerals, biomass, and fossil fuels could more than triple 316 Gt/year between 2016 - 2060, doubling GHG emissions and air pollution, driving catastrophic impacts from climate change, ecosystem collapse and impacts on human health, with limited damage to the economy mainly due to their method of estimating climate damages. In their resource efficiency scenario, they find that accelerated structural changes towards services could reduce materials extraction vis a vis the baseline by -80 Gt/year by 2060, while technology advancements within sectors could save an additional -68 Gt/year of materials, still resulting in a doubling of raw material extraction compared to the year 2017. Necessary next steps include introducing thermodynamic and biophysical consistency for production functions, material cycles and stocks, as well as the inclusion of demand-side measures and social heterogeneity. For LEMD scenarios, explicit representation of service provisioning would be required.

(Schandl et al., 2020) provide the first global modelling of economy-wide material use across five SSP scenarios using the GTEM-C model, a hybrid of CGE, a bottom-up energy demand model, and

GLOBIOM for land-use. They consider all primary raw materials grouped into metal ores, non-metallic minerals, biomass, and fossil fuels extraction summarized in 13 categories, and link them to corresponding economic sectors using material intensities (tons/$). Improvements in material intensities are applied to industrial sectors according to SSP narratives through careful deliberation by the authors. Industry is represented via a GTAP-MRIO-derived IO table with 21 sectors and 28 countries. Production structure changes result from labor and capital transformations in the CGE model. Recycling of non-metallic materials is addressed implicitly via regression functions and material intensities reducing primary material intensities in construction. The material intensities are a multiplier that links material input to sector output or added value and whose change is specified exogenously and does not affect the economic model at the core. Material stock dynamics and secondary materials are not explicitly modeled, as are physical services; demand is represented solely in monetary units. The low demand scenario implements SSP1, assuming high economic, but low population growth, with decreasing material intensities. They find that even in the SSP1 sustainability scenario, global raw material extraction could increase by ~50% to 143 Gigatons/year by 2060, further intensifying environmental pressures.

(Nong et al., 2023) use the GTEM-Resource model, a CGE model based on the GTAP-MRIO extended with raw material extraction data, to analyze West Asian policy impacts from resource efficiency and climate mitigation. Uniquely they introduce 'technology bundles' for three key industries—steel manufacturing, land transportation, and electricity generation. Each bundle consists of various technologies using distinct combinations of inputs, capturing practical constraints in substituting labor and capital between technologies. The study's scenarios include Resource Efficiency policy, Climate Mitigation policy, and a combined package. They find that even the most ambitious policy mix falls short in achieving absolute reductions in raw material extraction and GHG emissions, although relative reductions compared to a BAU scenario are observed. This work significantly contributes to LEMD modeling by integrating technological constraints and raw material extraction into a CGE framework but lacks full representation of material cycles and stock accumulation, as well as physical service indicators.

(Bachner et al., 2021) provide an innovative CGE-based modelling for three LEMD aspects: they explicitly model the demand for physical services, construct an alternative wellbeing indicator, and quantify co-benefits and avoided burdens, for the case of Austria. The study contains 9 measures spanning avoid, shift and improve for buildings and transport, and links them to Input-Output derived 74 sectors in a CGE framework. Their alternative wellbeing indicator is defined as the monetary sum of welfare effects (private and public consumption possibilities), co-benefits such as avoided air

pollution incl health impacts, and changes in leisure. They quantify the physical services buildings via a detailed energy-focused building vintage model in m² of floor area, and mobility via transport modes and travelled distances, which are later converted to monetary units via stock-flow-service relations. They note that the need for highly granular and diverse data is a limitation. They find increases in (alternatively measured) wellbeing in the climate transformation low demand scenario, while conventional indicators such as GDP are declining. For LEMD scenarios, extending this model with explicit material cycles linked to services, as well as expanding the coverage of service would constitute highly useful next steps to address material efficiency and circularity potentials across a larger set of services.

(Cao et al., 2019) couple a CGE model with a dynamic material stock-flow analysis for residential buildings in China, considering scenarios for service and stock saturation (m² per capita). Modelled construction material flows are fed into a CGE model to assess economy-wide feedbacks and rebounds, keeping GDP constant and ensuring both mass and monetary balances. Lower service saturation levels and delayed stock development could save up to 25.4 Gt in embodied CO2 emissions in the building construction sector, equivalent to 2.7 times the 2012 nationwide CO2 emissions. However, these savings are partially offset by increased embodied CO2 emissions in other sectors due to an economy-wide rebound effect (approximately 18.8 Gt or about 74%) due to the constraint that GDP remains constant and is re-distributed to other sectors. A physical description of the stocks and the services they provide creates a meaningful future description of service levels instead of the rather abstract description of investment and stocks in monetary units; next steps include expanding the soft-coupling of models to address material efficiency and circularity measures more systematically.

(Zhang et al., 2022) use a CGE model for Japan to assess how increased ICT use might impact GHG emissions and material demand. The model is based on the AIM/CGE (Japan) framework and is calibrated with the 2005 Input–Output Tables for Japan, encompassing 49 sectors and 43 commodities. The equilibrium is calculated year by year and capital stock turnover is explicitly modelled in monetary units. They focus on 36 ICT services spanning six industry categories, categorized into two groups based on their maturity and utilization rates, also including telework and online shopping. The results highlight that the adoption of ICT services, particularly AI-based ones, enhances productivity through labor-saving measures, contributing to GDP growth. This increased efficiency, especially in logistics and manufacturing, reduces oil and coal utilization, and slightly reduces demand from materials-intensive sectors, leading to some GHG emission reductions. For LEMD modelling, this research indicates how to model some aspects of ICT for socio-technical innovation in a very data-rich country. However, for full LEMD relevance, an expansion of scope to the

full supply chain impacts for ICT and an explicit modelling of at least ICT-related material cycles and physical service indicators would be required.

(Tong et al., 2022) couple the CGE model IMED with dynamic Material Flow Analysis to investigate global scenarios of the shift from internal combustion engines, to battery electric vehicles, and fuel cell vehicles, focusing on the supply and demand for platinum group metals. They explore three scenarios of different car stock saturation levels, structured via Multi-Level Transitions Theory. They highlight potential future mismatches between platinum group metal production, vehicle production, and end-of-life vehicles and give insights into the needs for global closed loop recycling systems. While the research explores the nexus between platinum use and CO2 emission reduction for car-based mobility, for LEMD modelling it would be useful to also consider other materials e.g. for infrastructure and charging, as well as modal shifts beyond cars and changes to the demand for mobility as well.

SoA in partial equilibrium LEMD modelling

(Grubler et al., 2018a) present the groundbreaking Low Energy Demand (LED) scenario covering the services of thermal comfort, consumer goods, mobility, food, commercial and public buildings, as well as upstream freight transport and industry activities, quantified via the partial-equilibrium energy system model MESSAGE. The LED scenario narrative is built around quality of life, clean local environments, widely accessible and novel (energy) services, urbanization, and information innovation via ICT, combined reducing energy and material demand while substantially increasing end-use service provision levels globally, particularly in countries with under-provisioning. Energy and material demand for end-use services were quantified "off-model" via the Avoid-Shift-Improve framework, combining intensified use of product stocks with material efficiency measures. These demand projections, together with SSP2 baseline information, were then fed exogenously into the partial-equilibrium energy system IAM MESSAGEix. Industry and bulk materials are treated specifically as an intermediate sector (with simplifying assumptions linking material needs to service demands in downstream sectors - buildings, transport, consumer goods). They assume that from 2020 to 2050, material use decreases by -20%, one-third due to dematerialization, and two-thirds due to improvements in material efficiency. Final energy demand decreases by - 40%, due to rapid electrification enabling rapid decarbonisation of the energy supply to stay within 1.5C warming with no CCS. Next steps would be an explicit, model-based representation of economy-wide material cycles, product stocks and end-of-life materials, enabling more systematic analysis of circular economy potentials, as well as path-dependencies and transformation requirements due to already accumulated material stocks and lock-ins.

(Tokimatsu et al., 2018) employ a bottom-up cost-minimizing energy model in the tradition of MARKAL and TIMES, to calculate metal requirements across energy technologies including hydrogen, for exogenously given energy demand levels. They model 2°C warming compliant climate policy scenarios, including 100% renewables. This analysis considers uncertainties related to future metal intensities, recycling rates, and energy technology stock lifetimes, drawing on experimental, process-based and LCA studies. Notably, the model incorporates sub-sectors like mineral extraction and processing, typically absent in energy system models. Unlike usual linear optimization climate/energy models, it incorporates material availability constraints over time, addressing measures such as technology lifetime extension, recycling, and material intensity reduction. They find that that all technology pathways result in similar warming levels without climate policies, but lead to emission peaks within a few decades under a 2°C policy. Metal requirements vary significantly across scenarios and uncertainties, with some metals, including Vanadium, consistently deemed critical in all outcomes.

(Zhang et al., 2019) model 40 supply-side efficiency measures in the iron and steel industry for China. They extend the PE IAM model MESSAGEix with an iron and steel module with high technological detail, which they drive with econometrically estimated exogenous 'use intensity' curves across intermediate and final end-uses in physical units and from macro-economic relations for infrastructure and machinery, assuming an overall decline of demand. They model material cycles partially, from raw materials to the demand for end-use products, considering also water use and air emissions. They introduce a constrained diffusion model of add-on technologies enabling efficiency measures, which have to operate jointly with a parent technology. They find that from 2010 – 2050, energy efficiency measures and route shifting could decrease raw material input by -14%, energy use by -7%, water consumption by -8%, CO2 emissions by -7%, NOx emissions by -9%, and SO2 emissions by -14%, respectively. Water withdrawal and PM2.5 emissions could increase by +14% and +20%. This study usefully shows how to improve the representation of technologies and supply-side material cycles, as well as multiple environmental pressures to explore trade-offs and synergies across impacts. For LEMD scenarios, an explicit representation of material stocks, subsequent secondary materials availability, as well as service provisioning indicators would be required to explicitly model demand-side considerations.

(Barrett et al., 2022) present a soft-coupled multi-model low-demand scenario for the UK. They start with the macro-economic model TIMES, enriched for industry by sectors using an MRIO, apply Material Flow Analysis for construction, buildings and the food industry, and a bottom-up transport model. In this 'whole-systems' model, industry demand is influenced by various factors, including transport services, construction (including building stocks and their lifecycle), and nutritional

requirements, as well as endogenous economic growth. It covers options to 'improve' energy efficiency, 'avoid' energy use and 'shift' to more efficient energy demand provision. A reduction of -52% in energy demand by 2050 compared to 2020 is reported as a result of technical and behavioral measures, without compromising wellbeing. This approach achieves data-rich scenarios drawing on pre-existing models, however not fully capturing material cycles beyond construction and buildings, therefore not capturing all material efficiency and circularity potentials, as well as eclectically combining different conceptual and theoretical foundations.

(Gaspard et al., 2023) conducted a highly innovative comprehensive multi-model analysis focused on sufficiency and efficiency measures for France's building sector, incl. implications for the entire economy as well as drawing on experts and qualitative surveys to develop scenarios, assess acceptability and inform new governance requirements. They combine econometrics, building stock turnover modeling, and bottom-up data for appliances, heating/cooling, industrial and construction activities, and waste management. They model various measures, including reduced floor space, less household devices, and adjustments of temperature settings for thermal comfort. They find that sufficiency measures could contribute significant energy savings, especially for domestic electrical appliances and space cooling, subsequently reducing industrial energy use, lowering demand for construction materials, waste and land take. The merger of qualitative and quantitative insights, as well as comprehensive multi-model coverage is very inspirational for LEMD modelling and shows how to develop country-specific, highly granular and directly policy-relevant LEMD insights.

(Sharmina et al., 2021) assess aviation, shipping, road freight and industry in ambitious emissions scenarios complying with 1.5-2°C climate limits, drawing on the partial-equilibrium Integrated Assessment Model IMAGE. Emission reductions for these sectors in the IMAGE model primarily come from deep reductions in energy- and GHG-intensities, but only minimal demand reductions. "Service demand" is operationalized via passenger travel (travel-money & -time budget) and per capita demand for freight ton-km. Demand reduction options are represented via stylized price elasticities, and for transport through the travel money budget concept. They assess potential demand reductions, including less air travel (aviation), reduced transportation of fossil fuels (shipping), more locally produced goods combined with high load factors (road freight), and a shift to a circular economy for industry, operationalized as distributed manufacturing and local storage; tightening standards for material use and product longevity. They show that demand-side opportunities are substantial, but are poorly represented in the model. Policy priorities include affordable alternatives to air travel, efficient transportation modes, speed reductions in shipping, lower demand for fossil fuel transport, and circular economy practices. For LEMD modelling, this exercise is highly useful to understand

transport, mobility, (global) trade and industry. Going beyond stylized elasticities constitutes a crucial next step, to capture how changes in material cycles and energy use affect trade and transport.

(Oshiro et al., 2021) employ a partial-equilibrium, technology-rich energy systems model AIM/Enduse for Japan, which is exogenously driven by GDP and population trends, to model low energy service demand scenarios. In the low demand scenario, the modelled measures encompass temperature control, reduced hot water usage, fewer consumer goods in the building sector, as well as the modal shifts, landscape transition, and cross-sector changes in the transportation sector. The industry sector is not linked to final demand, instead dematerialization and material efficiency factors (elasticities) are modified, similar to CGE models. Outputs of industry subsectors, such as cement, chemical, pulp and paper, and steel, are reported in Mt/yr, however without representing material cycles nor stocks. They find a potential of -37% reduction in final energy demand by 2050 through reduced energy service demand. If carbon capture and storage are excluded, mitigation costs increase significantly; which could be offset by lower energy service demand. Notably, reductions in industrial output and demand have the highest GHG mitigation potentials. However, the study lacks stock-flow consistency, relies on industry production estimates based on VA/GDP regressions instead of being driven by demand, and makes broad assumptions about material efficiency, with limited consideration of circular material use.

(Akimoto et al., 2022) utilize the DNE21+ partial-equilibrium energy system optimization IAM to simulate a worldwide transition to autonomous shared vehicles for private mobility-as-a-service", across 54 global regions. They use SSP1+2 baselines and quantify operational and industrial energy use, basic materials (cement, iron/steel, plastics) and GHG emissions, resulting from utilization, production and replacement of vehicles, and avoided construction of multi-story car parking. Their scenarios encompass increased car utilization, adjusted lifetimes, and slowed growth in travel distance demand. The model considers around 500 technologies, including equipment lifetimes, and assesses monetary costs and benefits associated with autonomous driving and car-sharing, e.g. safety improvements and time benefits, with services represented in person-kilometers. They find small potential reductions in the demand for iron, steel, chemicals, and cement, together with substantial reductions in energy demand due to more efficient mobility provision, resulting in substantial GHG reductions. Car- and ride-sharing emerge as significant opportunity for global emissions reduction with low or negative costs. The estimated marginal CO2 abatement cost in 2050 for a 2°C target is $169/tCO2. Future LEMD modeling should aim to systematically incorporate more transport modes and infrastructure requirements, as well as sector interactions and feedbacks (e.g. structural change in industry and its capital stocks).

(van Sluisveld et al., 2021) explore long-term decarbonization strategies for four emissions-intensive industries (iron and steel, clinker and cement, chemicals, and pulp and paper) within the partial-equilibrium energy system IAM model IMAGE. Material demand is derived from exogenous socio-economic drivers. Simple vintage stock models are used to model production capacities, technologies and investments. Simplifications of material recovery and recycling are included, while material stocks of iron and steel, as well as pulp and paper are explicitly covered. Scenarios are based on innovations literature, stakeholder workshops and systems engineering, focusing on changes in upstream and downstream industrial value chains, as well as if emissions are reduced or avoided. Scenarios focus on technology replacement, process efficiency, demand reductions via lifetime extension and material efficiency, as well as more recycling and industrial symbiosis between paper & pulp and chemical sector. All scenarios are flanked by a ramped-up carbon price forcing the model into 1.5°C Paris-compatible pathways. They find that the direct and indirect electrification of the iron & steel sector, carbon removal technologies in the clinker & cement sector, the closing of carbon and material loops in the chemical sector, and zero-carbon heating for the pulp & paper sector are critical for complying with climate targets. Residual emissions remain over the entire time horizon of the IMAGE model, with the pulp & paper sector as only exception. Next steps for LEMD modeling involve enhancing the representation of material life-cycles and stocks, and incorporating explicit physical service indicators.

(Lechtenböhmer et al., 2015) present technology-driven mitigation scenarios for a German province and assess how re-industrialization and energy-intensive industries can be aligned with the German Climate Protection Law. Three scenarios - best-available, breakthrough, and CCS technologies - achieve GHG reductions of 16%, 50%, and 79%. The study employs a technology-rich energy systems PE model and a simplified stock-flow MEFA model. The model relies on NRW's comprehensive industrial reporting to the European Trading Scheme and expert consultations for sector-specific data. The authors stress that technology alone, combined with unchecked material consumption, may not meet GHG reduction goals. Re-industrialization in NRW could impede Germany's energy and GHG targets due to limited efficiency potentials.

(Springmann et al., 2018) model how the global food system might comply with climate targets and other Planetary Boundaries, while providing sufficient biomass for healthy diets, and materials for industry and bioenergy. They use an adapted version of the global IMACT model (Robinson et al., 2015), which is a partial-equilibrium model of biomass production and consumption from agriculture, livestock and food-provisioning sectors, for 62 agricultural commodities, 8 food items, sectors/processing stages and 159 countries and their agricultural land availability and productivity. Demand is exogenously driven by population and GDP, while scenarios combine healthy and

flexitarian diets, food waste reductions and technological improvements; material demand from industry and bio-energy are assumed to remain at ~3% of global production. They find that no single measure suffices to keep the food system within Planetary Boundaries, and that a synergistic combination of measures is needed. While dietary change has largest impact on GHG emissions, technological solutions have highest impact on land use, water use, Nitrogen and Phosphor emissions. For LEMD modelling, this study shows very well how a well-defined service indicator ("healthy diet") can be translated to demand for materials (biomass), and subsequently energy use and GHG emissions.

(Deetman et al., 2021, 2020, 2018) conducted a series of studies that provide global material consumption under climate policy scenarios using the IMAGE model, particularly in relation to the electricity, buildings, vehicles, and appliances sectors. By coupling a dynamic stock model with the IMAGE framework, they systematically assessed material stocks, flows, and potential growth in material demand, especially in response to climate policy. Their analyses highlighted an escalating demand for materials, such as steel, aluminium, and neodymium, primarily driven by increasing electricity demand and a shift towards renewable energy technologies. Simultaneously, their focus on building stocks underscored the persistent growth in demand for construction materials, even in developed regions, and the limited potential of urban mining to meet this surge. Although these works do not provide insights into low material demand yet, they are critical steps for integrating material flows and stocks into IAMs, hence enabling the modelling of material efficiency and circular economy measures. As opposed to the conventional industry modelling in IAMs – where regional material demands are given based on historical trends of material use per GDP per capita – this approach provides biophysical consistency between the demand for materials services such as housing and mobility, and the demand for materials that is used as input in the industry sector module.

(Stegmann et al., 2022) provide the first IAM modelling consistently representing global plastic production, demand for plastic product stocks, and resulting waste, to assess how recycling and bio-plastics can mitigate global energy use and GHG emissions. They link a dynamic MFA model of global plastic production, stocks, end-uses and waste, with the IMAGE IAM based on the SSP2 scenario. They model competing uses of fossil fuels and biomass, as well as limits and opportunities of mechanical and chemical recycling. They find that bio-based carbon sequestration in plastic products, a combination of biomass use and landfilling can achieve negative emissions in the long term; however, involving continued reliance on primary feedstock. A circular economy approach without an additional bioeconomy push reduces resource consumption by 30% and achieves 10% greater emission reductions before 2050. A circular bioeconomy approach combining recycling with higher biomass use

could turn the sector into a net carbon sink, while also phasing out landfilling and reducing resource consumption. For LEMD modelling, this approach shows how to combine a dynamic MFA with thermodynamic and biophysical consistency with a PE-IAM, to assess trade-offs and synergistic measures. Next useful steps are looking into lower demand scenarios.

(Kermeli et al., 2022) demonstrate how incorporating dynamic material flow analysis of steel stocks and flows in a partial equilibrium model substantially improves future steel demand scenarios, using the IAM MESSAGE. Traditional steel demand estimations based solely on flow-based steel/GDP intensities overestimate future demand. When explicitly modeling steel stock-flow dynamics, end-of-life secondary steel availability for recycling, and assumed per capita saturation of steel stocks, they find that steel demand in 2100 could be 75% lower than in conventional flow-based estimations, using the same exogenous GDP and population drivers. While global steel demand projections are similar in the short-term, long-term projections differ between stock-based and flow-based approaches, because of the long lifetimes of most steel products, saturation dynamics, and the gradually increasing availability of secondary materials. For LEMD modelling, this work offers important insights into integrating a partial-equilibrium IAM with dynamic MFA; next steps are a deeper understanding of stock saturation levels, end-of-life flows and stock retirement dynamics, and the demand for physical services they provide.

Using the Global Timber Model, (Austin et al., 2020) quantify mitigation potentials and costs of forest-based abatement strategies (avoiding deforestation, forest management, re/afforestation and changing rotation lengths) under different carbon price scenarios. They find that avoiding deforestation plus afforestation have the largest mitigation potential, particularly in tropical regions, but rotation and forest management become more important in higher carbon price scenarios, especially in temperate and boreal forests.

(Daigneault et al., 2022) investigate the impact that forest management can have on the carbon sequestration and wood provision, by comparing results from three forest sector models (the global timber model GTM, the Global Biosphere Management Model GLOBIOM, and the Global Forest Products Model GFPM) across 81 SSP and climate mitigation pathway scenarios. They find that global forests could sequester 1.2-5.8 GtCO2eq/yr over the next century if forest management is improved, even when harvest increases and forest area does not expand. They argue that including practices of forest management in IAMs is an important next step to better represent the climate impact of wood extraction from managed forests.

(Costa et al., 2021) model European decarbonization and focus on integrating behavioral changes with technology advancements, based on a multi-systems IAM like model co-created with stakeholders.

The study employed the demand-driven European Calculator model to analyze the interplay of behavior and technology changes, revealing that behavioral changes could contribute over -20% of the GHG reductions required for net-zero by 2050. It is shown that ambitious behavioral and technological shifts, when combined, can accelerate the achievement of net-zero targets by approximately 2040. For instance, changes in travel behavior curb rising electricity demand and reduce infrastructure requirements. Moreover, adopting healthier diets substantially reduces emissions and frees up cropland for conservation or bioenergy production, thereby alleviating the trade-offs between energy and food. Regarding the modelling approach, the study's innovative aspect lies in its modular structure, encompassing multiple sectors with an intermediate level of complexity. While no new methods were introduced, the comprehensive scope and emphasis on the interplay between behavioral and technological changes sets this study apart. With regard to future research, the authors emphasize the necessity of macroeconomic consistency for assessing how lifestyle choices impact GDP scenarios and investments. In summary, this paper argues that an overreliance on technology deployment in Europe's climate efforts limits broader co-benefits, while incorporating behavioral changes can lead to earlier and more substantial GHG reductions, effectively advancing the timeline for achieving net-zero targets.

(Günther et al., 2019) model how multiple resource efficiency and demand-side measures can help achieve net-zero GHG targets in Germany. They present a technology-rich multi-model analysis driven by exogenous assumptions for transport, heating and cooling in buildings, agriculture and forestry, which then drive a PE energy optimization model, a waste module, and a global trade model. Climate protection and natural resource conservation require integrated actions, with a fossil fuel phase-out, transformation of the energy system, and transition to environmentally conscious lifestyles. With regard to low energy and material demand scenarios, for example, reducing the demand for extensive living spaces and retrofitting larger homes into sub-units, results in decreased land sealing, as well as reduced overall energy and material demand. Moreover, the report highlights that Germany should provide financial support, technological assistance, and knowledge transfer to promote global GHG reductions and resource use efficiency. Imported products must meet high standards for low GHG emissions and material efficiency, strengthening global change for climate protection and resource conservation. The most ambitious scenarios combining phase-outs, supply-side efficiency and technological progress, with demand-side measures and shows that until 2050, GHG emissions can be reduced by -95%, raw material consumption by -56% and final energy consumption by -24%.

(IEA, 2021) model how to achieve global net zero emissions by 2050 by coupling two partial equilibrium models for energy markets and energy technologies, whose results they use to drive

the GAINS model for global air pollution and health impacts, the GLOBIOM model to assess land use and net emissions of bio-energy demand, and the GIMF DSGE to assess how changes in investment and spending affect global GDP and financial markets. They model global scenarios including comprehensive supply- and demand-side measures between 2020 and 2050, including assessing criticality of materials for the energy transition. According to IEAs net-zero scenarios, around 55% of emissions reductions depend on demand-side changes and consumer choices, including increased uptake of e-mobility, speed limits, and a shift to high-speed rail instead of air travel. Industry decarbonization is modelled to occur slowly, due to investment cycles into fixed assets, short-term technological limitations and needed upscaling of negative emission technologies.

SoA in System Dynamics LEMD modelling

(Allen et al., 2019) employ the iSDG System Dynamics macro-economic model to simulate pathways for Australia to achieve the SDGs, incorporating large sets of supply- and demand-side measures. They nest their scenarios of 'inclusive growth', 'green economy', 'growth at all costs' and 'sustainability transition' in the SSP framework. The multi-sector model captures multiple non-linear feedbacks between 30 sectors/modules, covering economy-wide raw material extraction and final energy use, selected sectoral stocks (infrastructure and vehicles, land-use and soils, etc). They model GHG emissions and multiple environmental impacts, covering all SDG indicators. Key findings are that a 'Sustainability Transition' scenario achieves 70% progress towards SDG targets by 2030, surpassing 40% progress in a business-as-usual scenario. A focus on economic growth, social inclusion or green economy in isolation foregoes opportunities for greater gains. For LEMD scenarios this model seems highly useful and comprehensive, where improved coverage of material cycles and stocks, an overhaul of the Coub-Douglas production functions, as well as an extension of the SDG orientation through a service provisioning perspective, would enable major progress.

(Moallemi et al., 2022) utilize the global System Dynamics IAM FeliX to model low-demand pathways and their interactions across eight Sustainable Development Goals (SDGs). Interestingly, the model includes socioeconomic wellbeing indicators based on a capability's perspective, including the outcomes life expectancy and the Human Development Index. They model multiple interactions among the environment, the economy, and wellbeing, focusing on systems transformation pathways and the challenges and synergies for achieving the SDGs. While the model encompasses elements of the global social metabolism, including modules for population, economy, education, energy, water,

food, land, biodiversity, and climate, several aspects could be improved for LEMD modelling. For example, the industry/economy module could be enhanced by replacing the aggregate production function with a detailed input-output table, enabling a better coupling of demand to economic sectors rather than relying solely on aggregate GDP as driver. Material cycles and stocks are only selectively included in relation to land-use, while the financial and the transport sector are excluded entirely. A more systematic extension towards material cycles and service provisioning constitute important next steps for LEMD scenarios.

(Neumann and Hirschnitz-Garbers, 2022) use the System Dynamics framework ICARE to explore how a 100% renewable energy system globally impacts material reserves and utilization of bulk- and precious metals, drawing on the World Energy Outlook 2015 “New Policies Scenarios” to model scenarios for material efficiency, sufficiency and substitution. The model includes land-use and a simple game-theoretical model between a resource-supplying and a resource-importing region, and the dynamics between economic growth, employment and incomes. They find that improving recycling is essential to provide secondary materials, reducing potential economic constraints due to the depletion of high-grade raw material reserves associated with increasing costs. Potentials for GHG emission reductions were greater in material substitution scenarios than in material efficiency scenarios, because substituting abiotic for biotic materials increases ecosystem carbon sink functions. Changing diets and reducing food waste are essential to decrease biomass and land competition for food vs. material or energy use. For LEMD scenarios, expanding the service provisioning modelling as well as expanding the coverage of material cycles, stocks and end-uses beyond the energy system would constitute highly useful next steps.

(Sverdrup and Olafsdottir, 2023) extend the World7 System Dynamics IAM model by concrete and sand, including reserves, industrial processing, stock accumulation, energy use and GHG emissions, as well as covering various metal cycles drawn from previous work. Their model fully complies with the Laws of Thermodynamics for mass and energy. They compare a global low-demand scenario based on a saturation and eventual long-term decline of concrete stocks per capita, with a GDP-driven stock-growth scenario. They model energy system and industrial process decarbonization pathways, as well as improved recycling and material substitution options. They find that the long-term limitation for cement production is the availability of energy and reinforcement iron bars, requiring available iron and steel. While clearly a rapid decarbonization of energy supply and process emissions from cement production are necessary to achieve climate goals, substituting 50% of the cement with mortar appears possible, with high strength cement prioritized for those constructions that demand it. The availability limitation found will be that the cost for cement will go up significantly and decrease

demand. Improving end-use resolution as well as service provisioning beyond material stocks per capita proxies could make this approach highly useful for LEMD scenarios.

(Kumar et al., 2021) use the Sustainable Alternative Futures for India (SAFARI) model, a novel systems dynamics model that addresses dynamic inter-sectoral relationships and interdependencies. This study explores how urban built form and transportation impact resource demand, energy consumption, and GHG emissions. A highlight is the integration of a "decent living" dimension, explicitly addressing the gap in affordable housing and the associated construction requirements. SAFARI estimates demand in a bottom-up fashion. Sectoral growth primarily stems from essential development objectives, such as food and water security, universal housing, healthcare, education infrastructure, power access, and clean cooking and transport. Moreover, SAFARI incorporates a computable general equilibrium model to ensure macroeconomic consistency. The results of this study underscore the advantages of a vertically compact residential built form, combined with the use of less energy-intensive materials, like aerated autoclaved concrete blocks. When complemented by increased public transport usage and shorter trip lengths, this approach can significantly reduce residential land consumption, particulate matter emissions, embodied emissions of construction and space cooling energy. Overall, this scenario could lead to a remarkable 9.1–9.6% reduction in cumulative economy-wide greenhouse gas emissions between 2020 and 2050. From a modelling point of view, certain limitations exist, including the absence of a stock-flow consistent perspective for modeling housing cohorts and a comprehensive material cycle model. Additionally, there is limited validation with historical data. Despite these limitations, SAFARI represents an innovative framework for comprehensive interdisciplinary assessments of low energy and material demand modeling, particularly when considering quality of life-related material indicators and development goals.

SoA in Life Cycle Assessment LEMD modelling

The concept of DLS is increasingly used to assess the life cycle energy and GHG emission implications of the material satisfiers for provision of wellbeing. Recent studies have assessed the life cycle energy requirements for specific products and services, including housing, mobility, and nutrition, in a set of developing countries (Mastrucci et al., 2020; Mastrucci and Rao, 2019; Rao et al., 2019) and globally (Kikstra et al., 2021; Millward-Hopkins et al., 2020a). Most of these studies use LCA with detailed inventories for the dimensions directly linked to material use, while relying on MRIOs to address truncation errors and dimensions where the linkage with materials is less clear (nutrition, education, healthcare, and socialization) and linking with IAM to account for the energy supply system. These

studies have shown that food and transport dominate energy for decent living, while housing dominates upfront energy investment needs; across all service dimensions 156 EJ/year are needed after 2040, when infrastructure and building stocks are sufficiently expanded (Kikstra et al., 2021). Ambitious supply-side technology rollout, combined with demand-side measures where everyone converges to Decent Living Standards, could reduce global final energy use to 149 EJ/year, 60% lower than today (Millward-Hopkins et al., 2020b). Eradicating the material aspects of poverty by closing Decent Living Standards gaps especially in the Global South until 2050, would require structural and more equitable changes in energy growth and development pathways, while not necessarily conflicting with climate targets (Kikstra et al., 2021). Focusing on the material cycles and stocks for DLS, (Vélez-Henao and Pauliuk, 2023) provide a highly innovative modelling of disaggregated life cycle stages and product stocks in a counterfactual scenario, showing that nutrition and mobility at DLS globally, would require 6 [3-14] t/cap x tons of raw materials, and stocks of ~43 t/cap in buildings, some infrastructure and upstream industrial assets. These studies and models are highly useful for LEMD scenarios, with next steps ideally considering systematic consequential modelling for material efficiency and circularity strategies, and exploring pathways for a DLS-LEMD transformation from currently existing patterns of resource use and material stocks accumulated.

In a similar vein although built on different theoretical groundings, (Bjørn et al., 2018) investigate the required changes to household consumption and economy-wide production needed for Denmark to achieve its climate targets, for which they combine household surveys, attributional hybrid LCA-MRIO modelling of carbon footprints from global supply chains. They assess 10 different functions (living space, food, heating and lighting energy, mobility, public services, ...), the required products and supply chains, incl. steel and cement. They find that the emission intensities of consumption and production must be reduced by factors of 2-14, depending on future consumption levels. Their low demand scenario is derived from existing lifestyles and consumption patterns from surveys, primarily excluding travel by car and airplane as well as meat/beef, indicating high feasibility already today. Next steps for LEMD modelling include extension to material cycles and consequential/dynamic modelling of pathways. (Rammelt et al., 2022) operationalize 'just access' to minimum energy, water, food, housing and transport via physical indicators taken from the SDGs, differing in levels and scope from those used by the Decent Living Standards research, e.g. kwh of electricity, liters of water, kcal of healthy food, m² of living space, passenger-kilometers, and eclectically combine various attributional LCA factors. They show that in 2018, eradicating severe deprivation with current inequality, technology and behaviour, would amount to 2–26% additional impacts on climate, water, land and nutrients. They usefully expand their analysis to several Planetary Boundaries and show, that eradicating material deprivations for a third of the global population amounts to similar impacts as

due to the wealthiest 1-4% primarily on climate, highlighting the relevance of re-distribution for LEMD scenarios.

(Van der Voet et al., 2019) conduct consequential life cycle assessment of metals production for future energy scenarios, including future recycling potentials. They cover new technologies, ore grades, energy sources, and efficiency improvements in LCA foreground and background systems. In a business-as-usual scenario, GHG emissions are projected to increase 1.5-fold over today, while in the Equitability First scenario, total GHG emissions are 40% lower than current levels. Increasing secondary metals utilization in a more circular economy would reduce emissions substantially, but can be expected to become effective only in the second half of the twenty-first century when increasing amounts of end-of-life metals become available from ageing material stocks.

(Verhoef et al., 2018) use life-cycle process analysis to assess the potentials of additive manufacturing ("3D printing") for several sectors (Transport, Residential, Agriculture, Heavy Industry, Services, Non-energy use) to reduce global energy demand. They account for manufacturing efficiency and energy savings during the use phase, based on assumptions regarding energy savings related to material, transport, production, use, and maintenance, requiring further validation with field data. Energy savings of 5–25% are attainable in the aerospace sector, primarily due to weight reduction during the use phase. In the construction sector, savings of 4–21% are possible, with the greatest effects in feedstock, transport, and use phases. In a static extrapolation to 2050, this could reduce global energy demand by 26–138 EJ/year, equivalent to 5–27% of global demand.

(Buschbeck and Pauliuk, 2022) use dynamic LCA modelling to compare the climate impact of wood use under different forest management scenarios in Germany and inquire whether increased carbon storage in wood products and substitution of emissions-intensive products can offset forest carbon stock depletion (I.e., emissions) due to intensified management. To this end, they quantify the "required displacement factor" indicating the amount of emissions per ton that need to be substituted by wood, in order for wood to provide a beneficial climate impact compared to other materials, taking into account forest carbon dynamics under different harvest intensity scenarios, as well as more and less conservative energy decarbonization scenarios. Their findings suggest that in the short term (c. 25 years), the required displacement factors in the intensive wood harvest scenario are too high, while they are too low in the extensive wood harvest scenario to favor either strategy.

SoA in dynamic Material and Energy Flow Analysis for LEMD scenario modelling

(Krausmann et al., 2020a) provide a stylized modeling of global material stocks of major metals, cement, asphalt and other construction materials as exogenously driven by population or economic

growth, as well as for a low-demand contraction and convergence scenario. They show that in 2015, ~40% of global energy use and GHG emissions were required by industry, transport and construction for stock-building, and ~60% for stock utilization and service provision. They use historical trends of aggregate material- and energy efficiency gains and energy decarbonization to approximate supply-side measures, and for the low-demand scenario assume that stock levels in high-income countries in the 1970s suffice for high service provision. They find, that only the low-demand contraction and convergence scenario in combination with continued supply-side improvements complies with a 1.5-2°C carbon budget.

(Zhou et al., 2022) used dynamic MFA to study China, which is the world's main user of cement, aluminum, steel and ferroalloys, and modelled a Deep Mitigation Scenario with exogenously given >80% reductions in demand for new materials and lower manufacturing industry output based on assumed stabilization of Chinese material stocks. Future secondary materials supply could substitute large amounts of primary resource extraction and in combination with structural changes in Chinese industries, ambitious technological improvements in industry and aggressive energy decarbonization, more than 80% of GHG emissions from manufacturing industries could be mitigated; for the remainder they model ramping up carbon capture and storage to up to 100 $MtCO_2$/year.

(Watari et al., 2020; Watari and Yokoi, 2021) model global scenarios for six major metal cycles and their industries complying with a sectoral 2°C carbon budget for material production, assuming industry decarbonization, material efficiency and circularity strategies. They find, that ambitious high end-of-life recycling and product lifetime extension are by themselves not sufficient to meet climate goals and that a stabilization of global per-capita metal stocks at ~7 t/cap, half of that found in high-income countries is required, which includes a major reduction in high-income countries (Watari and Yokoi, 2021).

(Zhang et al., 2018) conduct a dynamic MFA for steel stocks in China, assuming future stock growth across many products, aggressive decarbonization and technological improvements in industry, resulting in slightly lowered steel demand and declining GHG emissions. They highlight the role of longer product lifetimes and the potentially massive oversupply with steel scrap, necessitating industrial restructuring, implementation of best available technologies and establishing effective recycling systems.

(Cao et al., 2020) model global cement production depending on future stock accumulation and investigate supply-side measures based on technology roadmaps. They show that re-absorption of carbon ('carbonation') by concrete stocks can result in a -30% reduction of GHG emissions associated with cement production. They find that ambitious technological measures are not sufficient to comply

with climate targets and that a stabilization and/or reduction of future stock levels, combined with carbon capture and storage, seem necessary. Subsequent work by (Cao et al., 2021) expanded the methodology to introduce technology and intervention richness across the cement and concrete life cycle, inclusive of low-demand measures such as materials-efficient designs, building lifespan extension, more intensive use, and component recovery and reuse. They find that demand-side materials reductions can largely obviate the need for cement plant CCS if pursued to their maximum technical potential.

(Song et al., 2023) model how China can achieve deep GHG mitigation via product lifetime extension and intensified use, as well as improved scrap recovery and recycling, across all bulk materials and multiple end-uses. Highly innovatively, they combine long term population and economic dynamics for all Chinese provinces, with life-cycle emission factors for material production with dynamic modelling of material cycles and stocks across multiple products and end-uses, incl. inter-provincial trade. They find that while differential economic development across provinces initially drives up the demand for material stocks, declining population and saturating demand eventually enables supplying the majority of material demand from recycling. Until 2060, improved scrap recovery cumulatively results in -10% GHG emissions, more intensive use which reduces demand for new products might reduce emissions by -21%. Lifetime extension offers only -3% reduction in emissions. Those strategies, which minimize material cycles and throughput by reducing material demand have great GHG mitigation potentials, particularly for materials without a viable recycling loop. This highly innovative study shows how to leverage the strengths of dynamic MEFA to assess supply and demand-side measures consistently across economy-wide material cycles and multiple product stocks. For LEMD scenarios, next steps are the inclusion of explicit service provisioning indicators as well as the energy required to use product stocks, as well as an extension to macro-economic implications and feedbacks due to such major structural changes implied.

(Watari et al., 2022) showed for Japan which already has substantial concrete stocks, that ambitious demand-side measures including resource-efficient design, lifetime extension, more intensive use, reduction of waste and improved end-of-life management can mitigate the 20% of GHG emissions associated with cement production remaining after all current and emerging supply-side measures have been implemented; minimizing the need for carbon capture and storage.

For the global stock of buildings (Pauliuk et al., 2021b; Zhong et al., 2021) and cars (Pauliuk et al., 2021b), a large set of supply- and demand-side measures were modelled to show how GHG emissions from material cycles and the utilization of, and service provision from, buildings and cars can be mitigated. (Zhong et al., 2021) coupled a dynamic MFA model, floor area, with consequential LCA into

a Partial Equilibrium IAM and used SSP scenario drivers, while (Pauliuk et al., 2021b) coupled a dynamic MFA, floor area and travelled distances with detailed energy and emissions data, using SSPs scenario drivers and the low energy demand scenario (Grubler et al., 2018b). Both studies find that even with aggressive supply-side technological decarbonization, substantial emissions remain. Material efficiency and demand-side measures, including longer lifetimes via re-use and repair, reduced floor space, material substitution (wood vs cement/steel), as well as ride and car sharing emerge as third pillar of mitigating climate change to 1.5-2°C of heating.

(Wang et al., 2022) model material efficiency, lifetime extension and improved recycling for copper cycles in the USA, using a dynamic MFA combined with Waste-IO for sectoral resolution, along with energy use and GHG emissions data from stock use. They model demand for housing (floor area per capita) and various appliances, population dynamics, and changing building archetypes based on an SSP2 storyline and the LED scenario by (Grubler et al., 2018b). For the example of refrigerators, they distinguish life cycle emissions from production and use phase. They emphasize the need to pay closer attention to the use phase when assessing circularity, particularly for products with high material and energy intensity during use, based on the refrigerator example. For example, extending the lifetime of lower-efficiency refrigerators, while reducing primary copper demand, leads to increased electricity consumption, resulting in a bigger net environmental impact. Overall, the material efficiency strategies reduce primary copper demand but elevate the often-neglected use-phase, ranging from 23–28% to 22–42%.

(Kalt et al., 2022) modelled the material stocks and flows required for energy system pathways sourced from the SSP-IAMC database, using dynamic MFA and consequential LCA to quantify bulk material demand and GHG emissions for production and construction of electricity infrastructures. Power plants require the majority of materials, while grid expansion and reinforcement require much less. Improved grids are crucial to accommodate volatile renewable power generation, as well as to provide universal access to electricity. In total, per-capita metal stocks in electricity systems are highly correlated with country-level indicators for the quality of electricity supply as well as the Social Progress Index (Kalt et al., 2021b). Improved material efficiency, technology choices, plant designs and technological development can reduce the demand for bulk materials considerably, as do measures reducing electricity demand.

(Ciacci et al., 2020) conducted dynamic material flow analysis, econometric regression analysis, and life cycle assessment to explore the future of copper demand scenarios in Europe until 2050, and the potential GHG emissions reductions due to a circular economy. They modeled demand through regression on population, GDP, and urbanization rate, considering various scenarios with green

technology and equitable lifestyle assumptions. The study's biophysically consistent copper stock-flow model includes recycling and associated GHG mitigation potential. The scenario emphasizing green technology and equitable lifestyles showed the lowest environmental impacts, with secondary copper flows converging with expected demand.

(Mayer et al., 2022) conducted a dynamic material flow analysis (MFA) and life cycle assessment (LCA) for the European food and land-use system, using the BioBaM-GHG 2.0 model (Kalt et al., 2021a). The model tracks agricultural biomass flows from ecosystems to final consumption of diets (kilocalories of different food products) in a biophysically consistent manner, including upstream energy requirements for agricultural machinery and fertilizer production. The study models low demand scenarios through alternative dietary options and variable non-food product demand for biofuels and fibers. Business-as-usual scenarios, constrained by a no-deforestation condition, result in land limitations and increasing GHG emissions. Agroecological measures can mitigate such negative impacts from food systems, but only if combined with a smaller-sized agri-food system, and if livestock systems are better aligned with regional feed production capacities. They show that LEMD measures in agri-food system have high potential to create synergies across multiple ecosystem services and create space for natural climate solutions and enhance land and food system resilience. .

(Bailis et al., 2015) quantify the carbon footprint of pan-tropical woodfuel supply and demand for subsistence cooking and commercial uses, using spatially-explicit information on supply, travel distances and demand. They assess woodfuel-related GHG emissions for 2009 by estimating the extent to which woodfuel demand exceeds biomass regrowth, integrating diverse evidence, including maximum travel distances and maps on aboveground woody biomass stocks, supply and demand, in an innovative way. Findings reveal that 27-34% of woodfuel harvested exceeds annual biomass regrowth in the ecosystems harvested, resulting in ~2% of global and ~4% of pan-tropical GHG emissions. The deployment of 100 million improved stoves could reduce these emissions by 11-17%, excluding all life cycle emissions other than from woody biomass stocks.

In an analysis of drivers impacting global forest carbon dynamics in 1990-2020, (Le Noë et al., 2021) quantify a number of counterfactual scenarios based on the CRAFT model (CaRbon Accumulaton in ForesT). The CRAFT model reproduces forest carbon stocks reported at low temporal resolution in forest inventories, based on an optimisation of parameters affecting the relationship between NPP and biomass carbon stocks, usually at national scales. In their analysis, they find that a “constant harvest” scenario would have reversed the observed C source of 0.74 GtC in 1990-2020 to a sink of 4.9 GtC, and a “no harvest” scenario would have increased biomass stocks by 49.1 GtC. While not

directly establishing links to consumption or needs satisfaction, this study points to the climate-change mitigation potentials of lowering wood use.

SoA in Agent-Based LEMD modelling

(Safarzyńska and van den Bergh, 2022) integrate an ABM into the DICE model by Nordhaus (Keen, 2021) to model distributional impacts of carbon taxes in a low economic growth scenario, thereby addressing potential socio-economic inequality effects. They find that unemployment has a high impact on the social cost of carbon, especially if high inequalities persist. Climate polices which should not come at the expense of social equity need to consider distributional effects across heterogenous poor and rich households. For LEMD scenarios, such a model can be useful to drastically improve heterogeneity of demand responses and distributional impacts.

(Yazan and Fraccascia, 2020) combine an enterprise input-output model with an ABM, to assess the potentials for industrial symbiosis which requires overcoming waste supply-demand mismatches and assessing potential economic costs and savings. They model the space of cooperation, defined as the operationally favorable conditions to operate industrial symbiosis, where the saved costs through industrial symbiosis are the main driver of the acceptance of incorporating the uncertainty that comes with potential mismatches of waste supply and demand. While their study is only conceptual, it provides high potential for data-rich applications to understand how more circular industrial systems might emerge, including shifts in supply and demand under a LEMD scenario.

(Koide et al., 2023) present an ABM to simulate how households and suppliers adopt and react to product-level circularity strategies, using a stylized product stock turnover model and LCA information to assess the resulting GHG emissions. They model consumer and supplier decision-making in response to repairing, refurbishing, functional upgrading, reusing, leasing, renting, and consumer-to-consumer (C2C) sharing. For LEMD scenarios this study shows how to leverage innovative combinations of modelling traditions, requiring data-rich empirical implementation and extension to service provisioning as next steps.

SI-5) Cross-cutting issues for all modelling traditions

In the following, we comparatively discuss several further important considerations across the modelling traditions, also drawing on important points from previous reviews, e.g. (Mercure et al., 2019; Pauliuk et al., 2017). Tthe theoretical assumptions underlying each model (incl. limits of monetary valuation, (in)commensurability, system boundaries), the methodological approach used to generate scenario results, the endogenous drivers of model dynamics (flow of information), the

granularity of industry and supply representations, as well as the heterogeneity of demand modelling (Table 2 for a summary).

Table 3: Preliminary summary of the assessment of nine modelling traditions vis a vis key LEMD modelling considerations.

	Non-equilibrium macro-economic models	**Econometric forecasting**	**Equilibrium macro-economic models**	**Input-Output analysis**	**Partial equilibrium models**	**Life Cycle Analysis**	**Material and energy flow Analysis**	**System Dynamics Models**	**Agent-Based Models**
Scope	economy-wide	economy-wide	economy-wide	economy-wide	sector	products and functional units	Products to economy-wide	Economy	Variable
Drivers	Demand	Supply	Supply-Demand	Demand	Demand	Demand	Both	Both	Both
Consistency	monetary	monetary	monetary	monetary, biophysical flows	Monetary, commodity specific biophysical	Biophysical, truncation errors	Biophysical stocks and flows	both	both
Simulation vs. optimization	Optimization	Optimization	Optimization	Simulation	Optimization	Simulation	Simulation	Simulation	Simulation
Sector / technological granularity	Low	Low	Low	Medium to high	High	High	Medium	Medium	Medium
Demand heterogeneity	Low-medium	Low-medium	Low-medium	Low-medium	Low	High	Low	Medium	High

The distinction between optimization and simulation seems particularly relevant for the modeling of mitigation options which are novel and disruptive and affect the timing when new technologies may enter the market. On the temporal side, optimization models can have different time horizons, ranging from a year-by-year optimisation (so-called myopic foresight) to rolling time horizons to inter-temporal optimisation. Simulation models are typically deployed with limited foresight, which means that information on technologies is limited at a certain time of the simulation. This is critical for modeling radically new technologies, as in radical deep decarbonization strategies, where simulation models display more inertia towards novel technology diffusion compared to optimization models which show an earlier market uptake. The introduction of novel technologies is however linked with the level of technological detail of an energy system as well as to a complex set of parameters governing the technology capacity and growth in the market.

Regarding theoretical assumptions, the macro-economic model traditions 1-4 can be grouped into two large groups depending on their theoretical assumptions on the existence of an equilibrium vs non-equilibrium. General equilibrium models assume rational actors which maximize their lifetime utility in efficiently working markets for all sectors in the economy; making these models elegantly solvable. Non-equilibrium models, on the other hand, allow for supply-demand imbalances such as overcapacity or unemployment, which requires additional assumptions or extrapolation of historic trends. Partial equilibrium then focus on specific commodity markets only, such as the markets for electricity or resources. The other modelling traditions can be primarily distinguished by their foundational principles rooted in biophysically consistent analysis (e.g., material and energy flow analysis, life cycle analysis), or their foci on non-linear feedback mechanisms and emergent system properties (e.g., system dynamics and agent-based modelling).

Regarding the approach to generating scenarios, one can either adopt a simulation or an optimisation approach; often, both approaches can be used in different parts of the same model. Simulation aims to reproduce the dynamics of a system via interpreting the principles of its operations, where the models represent the key behaviors and characteristics of a given process (in our case, industrial energy and material demand). The simulation allows the model to represent how the processes evolve under different conditions and assumptions over time, while including historic trends to the extent chosen. Simulation can be static if it describes the current system as a snapshot or dynamic if the current output is affected by evolution from previous periods. Simulation models can shed light on the endogenous relationship between variables to reproduce real world systems, and, although this may happen in a simplified fashion, they can also be rather complex. Typical applications of simulation models are exploratory or prospective analyses in non-equilibrium models, where the modeler starts with empirical model inputs and modifies them within reasonable ranges to determine what happens with the model outputs, which is very useful to explore a wide range of (in)possible futures. By tweaking the initial conditions, the behavior of the simulated system changes and can be observed. A class of simulation models, explores multi-agent approaches, interpreting the decision-making processes of key energy system players, which are suited to interpret market imperfections, consumer, and firm heterogeneity.

Optimization, on the other hand, is used to determine ‘optimal’ system design, choices and scenarios, which is widely used for climate change mitigation assessments. Differently from simulation models, optimization models provide the mathematically best solution for a given answer and set of criteria to optimize against. They consist of three elements: the objective function, decision variables and the constraints. Successful optimization depends on properly identifying the constraints placed on various

parameters—for example, the maximum level of energy from a given energy or emissions from a given source, at a certain cost and profits. Equilibrium models combine the optimization paradigm with the constraints that supply matches demand on the considered markets (equilibrium condition).

Depending on the description of the energy and industrial system in each model, which they contain, optimization and simulation models can be demanding in terms of computing power and time and can implement sensitivity analyses to explore robustness of results at different levels of complexity.

The variation of models along these three dimensions has important implications for modeling industrial energy demand and emissions. Non-equilibrium, simulation models allow the detailed study of the choices between the different sector-specific mitigation options. Yet, they often abstract from general equilibrium effects and are based on strong assumptions regarding the development of macro-level variables and indicators. This limits, for instance, the ability to model circularity practices which go beyond a specific sector or a specific geography or to understand the global implications of choosing different mitigation options in different sectors or countries. The opposite is true for equilibrium, optimization models.

In addition to these three key dimensions, several other aspects have been highlighted as relevant for the classification of models; often, these other aspects somewhat overlap, or are correlated, with the three discussed above. For instance, the literature often distinguished between bottom-up and top-down models. Bottom-up models are generally understood as integrating a high level of technical information in the characterization of industry (Herbst et al. 2012). Bottom-up here means, for example detailed data-driven “engineering type” descriptions the energy system, different industrial technologies, or the material and energy flows along the entire upstream and downstream supply chains for the detailed building stocks (Pauliuk et al., 2021a), often modelled via cohort/vintage models and clear descriptions of technological/biophysical constraints, prices, etc. The key strength of bottom-up models is the characterization of the interlinks between technology components based on the mutual dependencies of energy and mass flows. This feature enables them to provide in-depth analyses of sector strategies; however, it also determines their partial equilibrium nature, as they often ignore relationships between sectors. Disadvantages of bottom-up modeling are linked to data requirements and the exclusion of inter-sectoral feedbacks. Regarding the former aspect, modelers are largely reliant on data availability and trustworthiness to model technology diffusion, investments, and operational costs. The second aspect is the main criticism of bottom-up modeling, which concerns the failing to account for program costs, the feedback of energy policy and the lack of macro-effects of the assumed technology shift on general economic activity, structural changes, employment, and pricing.

Top-down models, on the other hand, describe technologies as a set of techniques by which inputs such as capital, labor, and energy can be transferred into useful output; they therefore give an aggregated description of the economic system, at the expense of less detailed technological variability (IPCC, 2022). Top-down here means simplified and aggregated descriptions of entire economies or sectors, for example when treating industry as a few sectors, which interact with final demand via aggregate production functions, which in turn are linked to energy and emissions via aggregate energy and emissions intensities of production and consumption (cite); similarly an aggregate modelling of global economy-wide societal material capital stocks, their operational final energy use and the required materials and energy for construction and maintenance (Krausmann et al., 2020b, 2017) would qualify as top-down modelling.

Top-down models have a high-level representation of social and economic behavioral relationships such as those between economic welfare, economic growth, and employment; they therefore enable a full understanding of energy policy effects on the economy of a region or a country (Herbst et al., 2012). However, given their inadequate technological detail and the inability to portray firm's and industry's heterogeneity, they are generally unable to provide an accurate picture of technical advancements, non-monetary hurdles to energy efficiency, or regulations for certain technologies. Top-down models are not suitable to portray credible technology prospects, especially as discontinuity would apply in the long run, when as a result of technological development and saturation, intra-sectoral structural change would occur (Herbst et al., 2012). Moreover, because top-down modeling approaches are based on the theory of efficiently allocating markets and rational actors, they tend to underestimate the complex nature of barriers and their non-monetary forms, such as institutional, historical and legal framework conditions, a lack of knowledge, insufficient decision routines, or group-specific preferences of technology producers or wholesalers.

Another relevant difference among models of industrial energy demand is the granularity and heterogeneity with which they characterize demand, energy use and emissions. Models can depict a single industrial sector aggregating all production activities (typically, this is the case of top-down models) or can specify a few key sectors of interest while lumping all other economic activities in the "other" category. Alternatively, models can be very detailed and include many sectors and subsectors (typically, this is the case of bottom-up models), or focus not on sectors, but on specific materials. There are several trade-offs associated with the choice of aggregate versus detailed representation. The more sectorally-detailed a model, the more it can depict differences between the various mitigation and energy-saving options within and across sectors. This of course can be achieved only if very detailed data is available to feed the model, and usually leads to very long computing times to

achieve a solution. Top-down models, on the other hand, are often limited in their portrayal of specific technologies and processes in the industry sector, especially of technology-driven structural change. This lack of technological information restricts the models' utility in analyzing technology-specific and sector-specific mitigation methods and policies. Top-down models also feature a highly aggregated depiction of industrial energy demand, making it difficult to evaluate demand-side mitigation techniques such as recycling, product-service efficiency, and demand reduction choices (Pauliuk et al., 2017).

Given these trade-offs, over time a larger number of models have adopted a hybrid approach, namely they include features of both top-down and bottom-up models. Sometimes, models also combine optimization and simulation in different modules, or they portray certain aspects of the economy at an aggregated level while they detail specific sectors of interest. Integrated assessment models (IAMs), for instance, often adopt a hybrid modeling approach of energy demand and emissions. Often, larger modelling suites like IAMs combine both bottom-up and top-down elements (Pauliuk et al., 2017). On the one hand, bottom-up elements can contribute more “realistic” representations, these are also highly data intensive to construct and update, and medium- to long-term projections might become problematic and/or constraint due to rapidly increasing uncertainty about the future. On the other hand, top-down elements can be better at representing generalized systemic relations and modelling longer term futures, however potentially relying more on the specific theoretical foundations and pre-analytical visions which are used to construct the model elements in the first place.

SI-6) Production functions in the reviewed literature

The tradition of LCA explicitly problematizes production functions as a value-laden choice: allocating physical production to consumption can be done via physical principles (energy contents, mass flows, volume) or monetary valuation (demand, profit) (Majeau-Bettez et al., 2016; Suh et al., 2010). Usually, LCA uses physical allocation principles and only uses monetary valuation as a secondary option. Capital stocks used in production are sometimes allocated over time across all products and services produced, which is a depreciation assumption which can follow physical lifetimes or monetary depreciation/value. MEFA uses biophysical units (mass, energy, land, stocks and flows). Typically, joint production of wanted (products, services) and unwanted by-products (waste, emissions) are modeled across supply chains and material cycles, which is not common in the other modelling traditions. The physical layer of capital stocks is explicitly modelled over time, in separation of the flows of materials and energy being processed, enabling analysis of the Stock-Flow-Service nexus, e.g., how configurations of stocks lock in flows of materials and energy required for service provisioning. Input-

Output Analysis uses a linear Leontief production function, constituting a fixed 'production recipe' showing how much direct and indirect production value across all sectors is required to deliver a final demand. This entails a monetary (value-based) allocation of resource use and emissions from production to consumption ('footprints'), where all direct and indirect sectoral contributions are covered, lacking substitution. IO also typically treats investments into capital stocks as a final demand flow, ignoring the contributions of existing capital stocks to production (Lenzen and Treloar, 2005). The so-called waste-IO-analysis (Nakamura and Kondo, 2002) allows for the mass-balanced description of waste treatment and recycling within the IO framework, including use of recycled material, and thus provides an important building modelling component of circular-economy-based LEMD assessments.

The macro-economic modelling traditions utilize a wide range of production functions, some of which are actually problematic for LEMD modelling as they violate mass and energy balances. The Cobb-Douglas production function claims that industry produces only using capital and labour, creating products out of thin air and without using energy. Widely used 'constant elasticities of substitution (CES)' production functions also assume perfect substitutability, even if they sometimes include energy or materials as production factors. This approach goes back to the Cost-Share Theorem and is clouded by the widespread assumption that everything can be sufficiently measured and allocated in monetary terms, effectively ignoring incommensurability issues. On the one hand, this means violating the biophysical consistency of joint production of wanted and unwanted (unintended) outputs. On the other hand, these production functions show how to endogenously model substitution between inputs and how to endogenously model technological and structural change, both of which are relevant for LEMD modelling. Some efforts are ongoing, especially in the non-equilibrium Ecological Macro-Economics tradition to develop thermodynamically sensible production functions (Capellán-Pérez et al., 2020; Dafermos et al., 2017; King, 2020; Sakai et al., 2019), although this issue is an ongoing debate.

SI-7) Detailed discussion of the research roadmap for improved LEMD scenario modelling

We derive eight suggestions for improved LEMD modelling from this review (see table SI-X for details).

1) **Interdisciplinary combinations of modelling principles and traditions yield more robust, nuanced and policy-relevant insights than any single tradition can provide**. Combining models requires carefully considering and potentially harmonizing differences in system definitions and modelling principles (see section 5.1.). Collaborating with the social sciences helps to understand how demand and service provisioning are organized, what acceptable and just low-demand futures could be like, and how they might be achieved.

2) **Thermodynamic and biophysical consistency** at high granularity across material cycles, energy use and material stocks across industrial networks and final demand is vital to understand time-dependent dynamics and efficiency potentials, e.g., shifts in consumption, product lifetime extensions, recycling potentials, electrification, etc. Ideally, appropriate data layers and units are combined, ranging from biophysical (tons, joules) to value of the capital, materials, age-structure, and capacity, as well as a detailed depiction of the technologies within industrial networks that primary (resource extraction), secondary (material production, energy supply, waste management, and manufacturing) and tertiary (service provision) sectors utilize. Economic, physical and social "layers" have their own rules of consistency (e.g., accounting & book-keeping rules, biophysical stock-flow relations, mass balance and the laws of thermodynamics, different forms and exergy content of energy, socio-ecologically constructed conceptualizations of wellbeing and required benefits from services), posing a challenge for combination. Energy use needs to be linked to material cycles, economic sectors, and material product stocks in a thermodynamically consistent manner, tracking different energy carriers and their exergy contents. Ideally this happens at the sector/industries/technology level incl. thermodynamically sensible production functions, as well as for end-uses and service provision. Ideally, a clear differentiation of primary, final and useful energy/exergy use at the sector level is achieved, so that shifts in energy carriers and technological changes in energy supply, as well as feedbacks from materials-oriented strategies such as the circular economy, material efficiency and the bio-economy on energy requirements can be properly depicted.

2) **Explicit stock-flow-service nexus:** Material stocks in products, buildings, and infrastructure serve as constituents for service provision, as they are used to transform energy and material flows into functions and services in a context specific manner (Haberl et al., 2019, 2017; Kalt et al., 2019). What constitutes a desirable and sufficient level of „low demand" is an open question requiring transdisciplinary approaches to derive socially justifiable targets. It is clear, however, that service-

stock-flow relations are crucial components of provisioning systems, thus LEMD scenarios need to depict those consistently. The efficiency of alternative service provision models via different stock-flow relations, as well as the industrial transformation required to achieve them, is thus at the center of mitigating resource and energy demand for climate change mitigation (Creutzig et al., 2021a) (Creutzig et al., 2021b). Using service indicators, in particular, opens up novel LEMD possibilities. Demand for functions & services is ideally represented in non-monetary terms to allow for establishing a physical link between human needs and service provisioning systems.

3) **Wider spectrum of supply and demand-side measures:** Widening the modelled solution space is crucial, acknowledging that LEMD transitions will induce dis-equilibrium, major structural changes, and early retirement of some capital stocks, e.g. coal-fired power plants, internal combustion engines. Widely modelled standard economic instruments are subsidies and taxes, while coverage of behavioral responses is often limited to (bounded) rationality assumptions, both combined in optimization settings. Strengthened regulations, product standards, phase-outs, eco-design, extended producer responsibility, changes to settlement patterns (Haberl et al., 2023), transformations of the structural conditions for everyday living (APCC, 2023), as well as non-rational concepts of behavior are, however, highly relevant to understand emergent transition dynamics, which might need to be explored via simulating pathways not constrained to cost-optimality or rational choice. Because industry is inherently linked to labor, skill demand, monetary capital, as well as materials and energy, a multi-layered assessment of these processes is critical for outlining benefits and trade-offs of LEMD transition pathways. Applying the frameworks and other innovations presented in this work will help achieve consistency in scenario modelling of a wide spectrum of supply and demand-side measures, so that their overall potential, co-benefits, and trade-offs across multiple SDG indicators can be consistently assessed.

4) **Assess telecoupling in global supply chains and between industrial sectors:** To capture system-wide effects of demand-side changes and innovations in service provision, global supply chains and sector interactions need to be modeled systematically to detect potential rebound effects and burden shifting across the life cycle of products occurring between different sectors of the economy in different parts of the world. Because industrial processes require fixed assets for their functioning (factories, machines, tools, etc.), representing large capital investments and material stocks, a low demand transformation of industry requires capital modification and replacement, new skills, and often additional material resources. The different functions of industrial assets (capacity, capital, material stocks) as well as the different stages of the supply chains (resource extraction, material production, manufacturing, waste management, recycling, energy supply and service sectors) should

therefore be explicitly represented to consider capital constraints for LEMD scenarios and potentially global re-allocations of capital, labour, and natural resources in global supply chains.

5) **Assess resource constraints, vulnerability, and resilience of the global industrial network:** Modelling should address the complex socio-ecological dynamics, feedbacks, and non-linearities inherent in LEMD transformations. The environment is more than a repository of resources to be extracted and a sink for waste and emissions; complex trade-offs between different environmental aspects such as climate change mitigation, the biodiversity crisis and other planetary boundaries should be considered, as do negative feedbacks and limits for societal transformation pathways. Currently, a significant number of reviewed studies does address some non-climate impacts; these potentials should be extended. Already a number of transformative trends are impactful now, and will only become more relevant; these include: digitalization, pro-sumers (shifting system boundary of industries), X as a service, supply-chain shocks triggered by extreme weather, conceptualizations of low demand futures with high wellbeing, etc. A sufficiently complex representation of the global biosphere and its responses and feedbacks on industrial networks therefore is a crucial research frontier for LEMD modelling.

6) **Improved research infrastructure and community standards, building on open data and open science** principles are needed to facilitate consistent LEMD modelling and evidence synthesis across disciplines, institutions, modelling cultures, and data providers. Open science principles are crucial for cumulative, interdisciplinary sustainability science (Hertwich et al., 2018; Pauliuk, 2020), as are FAiR publications, where results should be Findable, Accessible, Interoperable, and can be readily Re-used (Wilkinson et al., 2016). This translates into the need for more data transparency, regarding baseline materials and emissions included in the respective study, product energy efficiencies and material composition, as well as savings per strategy modelled, to understand modelled reductions vis a vis the realized social metabolism. Comparing against BAU growth scenarios and only reporting relative improvements is not useful. Ideally, open code and open data are therefore implemented to facilitate knowledge accumulation for LEMD transitions. The number of national and sectoral scenarios and studies that were collected as input to the 6th assessment is significantly smaller than the global integrated emissions scenarios and will require additional sustained efforts in the next IPCC cycle and beyond to bring the coverage of national and sectoral scenarios to a similar level as the global ones. This includes developing and coordinating community standards for reporting, standardization of system boundaries and variable definitions and building up capacity to apply these modelling, accounting, and reporting standards across the different communities, particularly as relates to explicit representation of energy and material service indicators. Within the Integrated Assessment

Modeling Consortium (IAMC)[2] efforts are ongoing to broaden coverage of the aspects addressed by national and sectoral studies and to share experiences and improve capacities across communities in this direction. In the transport modeling community, the International Transport Energy Modeling (iTEM)[3] network is organizing workshops and coordinating efforts on harmonized data collection. The Energy Demand changes Induced by Technological and Social innovations (EDITS) network[4] organizes data collection, sharing and comparison activities across demand-side modeling communities, in order to improve coverage of these aspects in the upcoming 7th assessment cycle of the IPCC. Therefore, we see a strong need and benefit for LEMD modelers for adopting the requirements and standards for contributing their work to IPCC and other relevant assessments very early on in their research design, so that the necessary adjustments to the scope and resolution of and data reporting from the utilized modelling frameworks remains feasible to implement.

7) **Connect to ongoing efforts to improve the Shared Socio-economic Pathways** (SSPs) frameworks is important, so that future LEMD scenarios can be easily integrated into evidence synthesis by IPCC and others. The SSPs constitute the overarching framework for connecting climate change research across research communities, including climate change impacts, adaptation, vulnerability, and mitigation, which are used by the majority of reviewed studies. Many applications as well as regional and sectoral extensions of the SSPs that interpret and enrich the original narratives narratives (Ebi et al., 2014; Kriegler et al., 2014; O'Neill et al., 2014; van Vuuren et al., 2014) with additional detail have been published since the framework was released in 2014 (Green et al., 2022; O'Neill et al., 2020; van Ruijven et al., 2022). In July 2023, a quantitative update of the basic elements of the SSPs was published for community review[5], with revised updates expected to become available by 2024. More fundamental revisions of the narrative and scenario framework are being discussed. We therefore encourage future LEMD modelling efforts to draw on the latest version of the SSPs to increase consistency with the integrated scenario literature, including ongoing developments towards developing low-growth/low-demand SSP variants, thus increasing the evidence base for LEMD scenarios and making them more straightforward to use in global assessments and syntheses. Defining explicit and quantitative service provision level assumptions associated with each low-demand variant, and within each demand sector, will be critical for both linking low-demand SSPs to LEMD models and ensuring comparability across LEMD modeling efforts, first efforts are ongoing (Fishman et al., 2021). One key challenge for newcomers to the IPCC scenario submissions is to structure their

[2] https://www.iamconsortium.org
[3] https://transportenergy.org/
[4] https://iiasa.ac.at/projects/edits
[5] https://depts.washington.edu/iconics/, https://www.iamconsortium.org/event/iconics-and-iamc-joint-webinar-shared-socioeconomic-pathways-ssps-update/

modelling framework so that enough consistent data can be reported, to enable comparison to larger scale models while still being specific to individual countries or sectors.

Table SI-6: Synthesis of core aspects for industry modelling of LEMD transformations addressed in this review.

Modelling needs	New modelling principles
Technology-rich networks of industries linking extraction, to use, to end-of-life stages	Fully represent material cycles, ranging from extraction, manufacturing, service sectors, and waste management with sufficiently high detail
Materials focused strategies need to be assessed for their implications on energy use and emissions	Link material cycles with useful energy use at sector level to fully show potentials and limits of strategies such as the circular economy and the bio-economy, e.g. re-use, re-purpose, repair, refurbishment, recycling, downcycling.
Large existing material stocks and capital assets constitute lock-ins and inertia for a transformation	Depict industrial assets and material stocks on multiple layers: value of the capital, materials, age-structure, capacity, utilisation, fixed and variable costs, …
Depict material stocks as constituent for service provision, for production and consumption, and for future secondary resource deposits	Trace material stocks in products, vehicles, buildings, and infrastructure and their link to service provision consistently with material cycles, to understand time-dependent dynamics, lifetime of stocks, and future recycling potentials.
Biophysical supply-demand consistency	At aggregated level (transport, buildings, infrastructure, public and private consumption) and per service type (individual, public transport, etc….)
Industrial processes are linked to labor, skill demand, monetary capital, as well as materials and energy	A detailed and multi-layer (economic, physical, social) assessment of industrial process is needed to depict possible transition pathways
Industry links to demand for functions & services in non-monetary terms	Final demand by households and its contribution to wellbeing consists of materials and energy services required to perform certain functions and activities, ranging from housing, adequate nutrition, social signaling, etc. These considerations are not properly covered in costs and prices (monetary valuation).
Explore a larger range of strategies and possible futures	detailed policy modelling (subsidies, regulations, phase-out, eco-design, etc.), economic (business model assessment), and behavioral options (adaptation of new businesses or lobbying against change) is needed.
Link environmental and social impact assessment	green growth alone will not result in better societal conditions and needs to be compensated with social policies that directly tackle inequality (Cieplinski et al., 2021)
Marginal and cost optimal changes are not sufficient for LEMD futures	Ideally, LEMD industry modelling can address non-linear changes, as well as disruptive & structural transformations
Socio-ecological trade-offs, feedbacks and biophysical limits are widespread, e.g., damage functions, limits, constraints, boundaries.	Feedbacks and limits due to natural systems, depiction of potential negative impacts from climate change and biodiversity loss, resource limits, ecosystem degradation.
System definitions and boundaries, consistent indicators	Document the exact system definition used in your study, e.g. which supply chains/industrial activities and strive to be compatible with commonly used system boundaries, variable/indicator definitions, and reporting templates.

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EDITS

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Material Cycles, Industry and Service Provisioning: A Review of Low Energy and Material Demand Modelling and Scenarios

Contribution to the EDITS project: review of industry modelling and low energy demand data

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1. Introduction

This review addresses two concerns: Firstly, recent global assessment reports have clearly established that mitigating greenhouse gas (GHG) emissions and environmental impacts requires directly addressing the scale and composition of socio-economic material cycles and accumulated material stocks of buildings, infrastructure and machinery (IPBES, 2019; IPCC, 2022; UNEP-IRP, 2019). Improving energy efficiency and decarbonizing energy supply and industrial processes alone does not suffice to comply with internationally agreed upon efforts to limit the increase in global mean temperature to 1.5-2°C above pre-industrial levels (IPCC, 2022); furthermore, it does not address non-climate environmental impacts driving the transgression of five Planetary Boundaries (Richardson et al., 2023). Economy-wide material cycles include raw materials that originate from agriculture, forestry and mining and are processed by industry, manufacturing and construction; they include transport and waste management and, ultimately, final product demand, which accumulate as in-use material stocks (Haberl et al., 2019; Pauliuk and Hertwich, 2015). Material production and industry activity accounts for 20-34% of global GHG emissions (Hertwich, 2021; Lamb et al., 2021); material extraction is an important driver of land use change and biodiversity impacts (Giljum et al., 2022; UNEP-IRP, 2019). Crucially, recent reviews showed that many macro-economic Integrated Assessment Models (IAM) regularly violate the Laws of Thermodynamics and lack the granularity, resolution and framework to fully depict material cycles and material stocks (Bataille et al., 2021; Pauliuk et al., 2017; Stern, 2011). These gaps critically limit our understanding of the potentials, trade-offs and multi-SDG impacts of strategies aiming to reduce, slow and close socio-economic material cycles (Aguilar-Hernandez et al., 2018; Creutzig et al., 2022; Hertwich et al., 2019; Hickel et al., 2022; McCarthy et al., 2018; Muscat et al., 2021).

Secondly, global assessment reports have clearly established that expanding the solution space to demand-side measures and service provisioning is necessary (IPBES, 2019; IPCC, 2022; UNEP-IRP, 2019). Demand-side measures – defined as (Creutzig et al., 2021a): '*mitigation opportunities that involve individuals or industrial end users of products, services or processes.*' – aim to avoid, shift, and improve service provision to achieve Lower Energy and Material Demand (LEMD). (Wilson et al., 2022) state: "*Demand-side strategies change how services are delivered (e.g., more energy-efficient end-use technologies and infrastructure, digitalization, business models to increase efficient utilization of resources). […] Supply-side strategies change how resources are converted (e.g., precision agriculture, decarbonization of power production) [...]".*

Service provisioning for human needs and societal wellbeing can be grouped along material needs for food and water, mobility, shelter, thermal comfort and lighting, health, education, entertainment, social interaction and participation. All of these require material and energy flows as well as material stocks of products, infrastructure and buildings, resulting in waste and GHG emissions (Fell, 2017; Gough, 2015; Kalt et al., 2019; Lamb and Steinberger, 2017). Related research streams grounded in different theories about society and social change include, for example, sufficiency (Jungell-Michelsson and Heikkurinen, 2022; Sandberg, 2021), post-growth (Jackson, 2017; Hickel et al., 2021), steady-state economics (O'Neill, 2015; Victor, 2022), sustainable consumption corridors (Fuchs et al., 2021), as well as degrowth (Kallis et al. 2018; Hickel et al. 2022), and the circular economy (Aguilar-Hernandez et al., 2018; McCarthy et al., 2018). Independent of one's favorite theory, LEMD substantially increases the feasibility of addressing the climate crisis without relying on unproven large-scale negative emission technologies, reduces the costs of mitigation and decarbonization, and contributes to improving societal wellbeing (Creutzig et al., 2022, 2021b; Grubler et al., 2018b).

So far however, most climate change mitigation scenarios limiting climate heating to 1.5-2°C assume

unprecedented efficiency improvements and rapid decarbonization of energy supply and other sectors, as well as gigantic amounts of negative emissions which is highly risky and prone to moral hazards (Anderson and Peters, 2016; Minx et al., 2018; IPCC, 2022). Most mitigation scenarios also assume endless economic growth and ever-increasing consumption, while perpetuating global inequality (Hickel and Slamersak, 2022). Existing mitigation scenarios report hardly any reductions in energy demand, partially because the underlying models lack heterogenous demand representations and usually do not consider service provision (Edelenbosch et al., 2020). They therefore explore only a narrow part of the solution space for sustainability transformations (Hickel et al., 2021; Keyßer and Lenzen, 2021; Lamb and Steinberger, 2017). Recently, the seminal 'Low Energy Demand (LED)' scenario with high service provisioning globally (Grubler et al., 2018b), as well as the dedicated IPCC chapter on services, demand and social aspects of mitigation (Creutzig et al., 2022) kick-started research into viable 'low-demand' futures with high wellbeing around the world, without resorting to technological silver-bullets.

This review addresses these concerns by surveying recent innovations in models aiming to address material cycles and stocks, industries, energy supply and GHG emissions, as well as final demand and service provision. We focus on Lower Energy and Material Demand (LEMD) scenarios and the underlying models. We do not aim for a general synthesis of mitigation potentials, which was recently done by (IPCC, 2022). *Herein, we summarize the status and research needs for modelling material cycles and industry in LEMD scenarios, answering the following research questions:*

- *Which aspects, principles, and system linkages of material cycles and industry need to be covered for LEMD scenarios and how are they addressed in the literature?*
- *How is service provisioning and its link to industry conceptualized and operationalized in the recent and relevant modelling literature?*
- *Which potentials of supply- and demand-side measures for LEMD have been shown so far?*
- *Which recommendations for modelling industry and material cycles for LEMD scenarios emerge?*

Literature deemed relevant was identified between 03/2022-09/2023 from scientific literature databases and via citation snowballing, to identify fully relevant and innovative studies, which aim to a) have biophysical and thermodynamic consistency between material cycles and stocks, energy use and GHG emissions, 2) treat industry not as end-user but as delivering to intermediate and final demand, 3) model demand and service provisioning ideally in non-monetary units, and 4) model scenarios with low(er) demand. We focused on recent, noteworthy studies published between 2014-2023, screened over 300 studies and selected 75 for in-depth review. We grouped all included studies according to their main modelling tradition, and assessed model scopes and results detail, including their operationalization of "service provisioning", using the Energy Service Cascade (Kalt et al., 2019) and the Stock-Flow-Service Nexus (Haberl et al., 2017) as analytical frameworks. Additional documentation about the research design and methods, as well as the full assessment of studies can be found in the supplemental information and data file.

2. Principles and purposes of the nine modelling traditions

We identify nine industry modelling traditions, each developed for specific purposes and based on different worldviews, theories, and modelling principles (Figure 1). For an introduction and overview for each tradition, we refer to the supplemental information section 2. These different foundations result in diverse terminologies, system definitions, model scopes and aims, data requirements, and computational complexity. Modeling society-nature interactions began in the 1960s, spurred by concerns about environmental degradation, energy security, and climate

change, and the establishment of UNFCCC and IPCC. Macro-economic IAMs were developed to simulate emission scenarios and mitigation strategies, grounded in fields such as Energy- and Environmental Economics (Figure 3, in green). Alternative socio-ecological approaches focusing on a biophysical, non-monetary systems perspective emerged between the 1960s and 1990s, grounded in fields such as Industrial Ecology, Sustainability Science, Ecological Economics, and Complex Systems Science (Figure 3, in yellow).

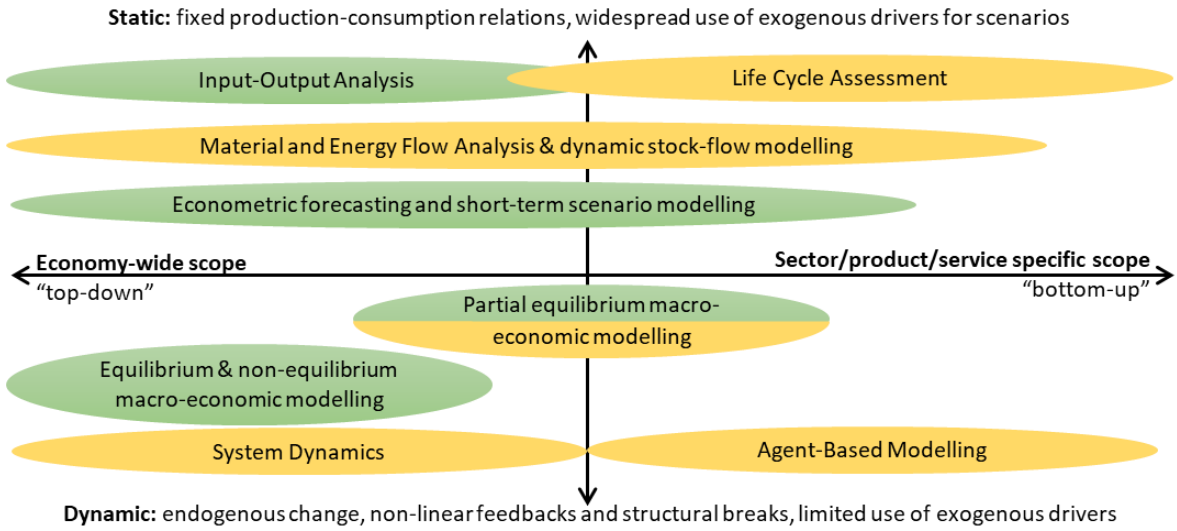

Figure 1: Foundational principles and typical scopes of the nine modelling traditions reviewed herein. Traditions in green originate from Energy and Environmental Economics, while yellow traditions originate from Engineering, Industrial Ecology, Ecological Economics, Socio-Metabolic Research and Complex Systems Science. The positioning of each tradition is based on the authors domain expertise and is only meant to provide orientation. We refer to the supplementary information for a more detailed discussion and literature sources for each tradition.

3. State-of-the-art models for LEMD scenarios

We identified 77 relevant studies published between 2014 – 2023. Two-thirds operate within their tradition, while one-third combines methods and data from engineering, Industrial Ecology, Ecological Economics and Complex System Sciences ('biophysical+'), ABM and other traditions ('ABM+'), as well as biophysical and macro-economic modelling ('economic+biophysical'; Fig.**Errore. L'origine riferimento non è stata trovata.**a). Most s tudies have national, world-regional, or global scopes (Fig.**Errore. L'origine riferimento non è stata trovata.**b). Two-thirds of regional and (sub)national studies focus on the Global North, while only one-third specifically investigates the Global South (Fig. SI-3). Around two-thirds of the reviewed studies are published Open Access and have supplementary information (Fig.**Errore. L'origine riferimento non è stata trovata.**c). Only one-third p rovides machine-readable supplementary data and a mere 10 studies (13%) provide open model code, hampering assessment, comparison and evidence synthesis.

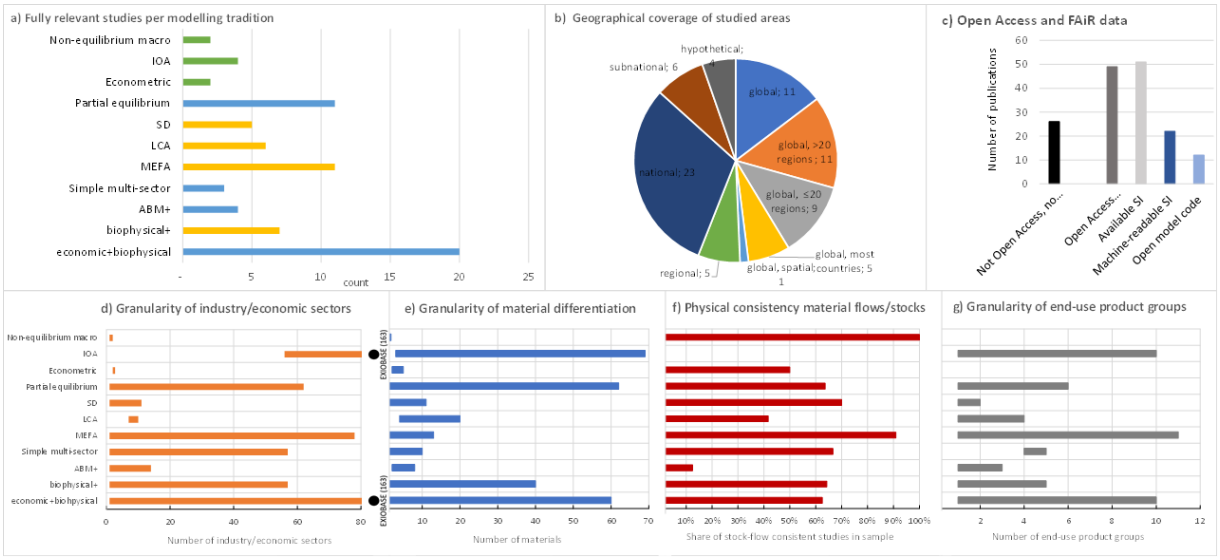

Figure 2: Overview of relevant studies by tradition and emergence from original research fields (a) coverage of geographical scopes (b), and implementation of FAiR open science principles across the reviewed literature sample (c). Ideally, studies, results and model code should be Findable, Accessible, interoperable and Re-usable (FAiR)(Wilkinson et al., 2016). Further documentation on coding and assessment can be found in the supplemental information section 2.

We find substantial differences in the resolution and granularity of industries and economic sectors modelled across the traditions (Fig.**Errore. L'origine riferimento non è stata trovata.**d). Especially MRIOs and those using u nderlying data stand out, as they have been specifically developed to provide detailed sectoral classifications for extractive, manufacturing and service industries, with EXIOBASE at 200 products or 163 industries (Stadler et al., 2018), and GLORIA with 120 sectors (Lenzen et al., 2021). Others like WIOD or GTAP have lower resolution of 35-64 sectors. Models from the MEFA, LCA and SD traditions usually focus on specific industries and/or materials, resulting in relatively lower sectoral resolution, although recent synthesis studies compiled high resolutions of up to 78 industries/sectors. For the macro-economic traditions, we find an intermediate sectoral resolution of 1 – 57 sectors.[1]

MRIOs (69), partial (62) and general (60) equilibrium models, as well as model combinations using input-output tables (biophysical+, economic+biophysical) are most detailed in covering materials. Depending on scope and aims, some of these studies aggregated to only 1-3 materials (Fig.**Errore. L'origine riferimento non è stata t rovata.**e). For the other traditions, we find low (1-8) to intermediate (10-20) materials granularity. Regarding biophysical stock-flow consistency, we find that both non-equilibrium studies model material stock-flow relations, however only stylized. For MEFA, biophysical consistency is the core principle (some MEFA studies only look at either stocks or flows though). In contrast to the relatively higher resolution and granularity found for MRIOs, we find that they only partially comply with biophysical stock-flow consistency (Fig.**Errore. L'origine r iferimento non è stata trovata.**e): while environmentally-extended input-out analysis enforces mass-balances, it

[1] Please note that the granularity of some studies based on LCA/MRIO combinations, which have substantial sectoral resolution in their 'background system', could not be assessed due to lacking documentation of the aggregation and truncation decisions common in LCA.

does not account material stocks, only specific variations account waste-by-products (waste and physical input-output analysis), and limitations arise from combining monetary and mass units (Streeck et al., 2023a). Regarding the coverage of modelled end-use product groups, we find that MEFA, MRIO and combinations of economic and biophysical traditions cover the most with between 10-11 end-use products groups (Fig.**Errore. L'origine r iferimento non è stata trovata.**f**Errore. L'origine riferimento non è stata trovata.Errore. L'origine riferimento non è stata trovata.**). Studies of the non-equilibrium macro and econometrics traditions do not model the number or material cycles of products explicitly, but depict resource use as intensity of macro-economic variables (e.g., per unit of aggregate or sectoral GDP).

When it comes to service provisioning, we find that across all studies what is most often modelled are end-use product stocks (amounts, weight, …) of appliances, food, motor vehicles, construction and residential buildings (Figure 2a). In summary, 'building & construction' is most often covered, followed by 'transport & vehicles'. For actual functions as physical 'action', the most prominent categories are housing, passenger transport, nutrition, heating and cooling, non-residential floorspace and freight transport (Figure 2b). Services as 'what is actually demanded' are substantially less quantified, mostly via employment and Decent Living Standards (DLS) (Figure 2c). Welfare, well-being and co-benefits are often approximated via GDP (Figure 2d).

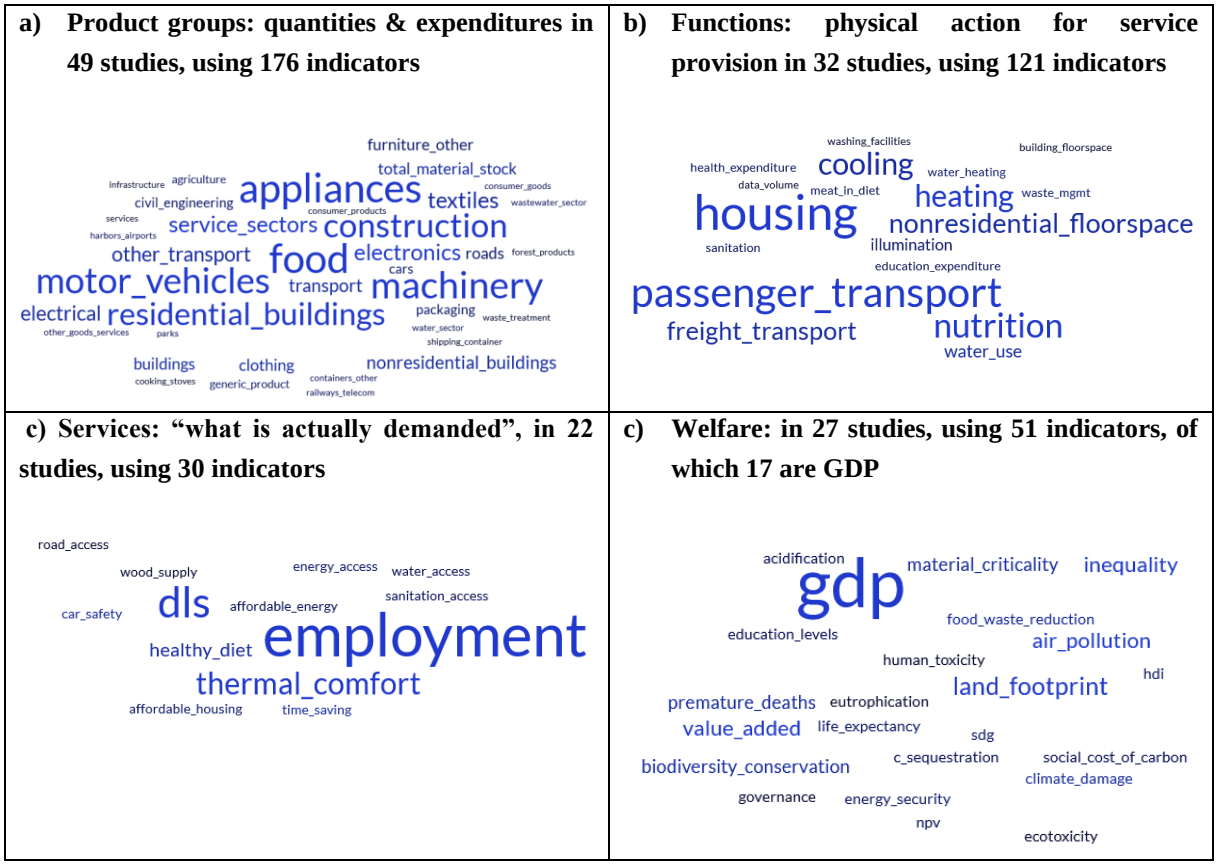

Figure 2: Indicators for product groups, functions, services and welfare & co-benefits used in the reviewed literature. For this grouping, we draw on the Energy Service Cascade (Kalt et al., 2019). *We add welfare & co-benefit indicators which are defined at macro-level. For details on the definitions, accounting methodology of the cascade elements, and counts by item please see supplemental information section 2.*

3.1 State-of-the-art in non-equilibrium LEMD modelling

We identify substantial novelty in the emerging field of stock-flow consistent (SFC) Ecological Macro-Economics, which so far has mainly dealt with energy and GHG emissions (Jackson and Victor, 2020; Jacques et al., 2023; Nieto et al., 2020). These studies aim to use thermodynamically appropriate production functions including energy/exergy and materials, also complying with stock-flow consistency. Extending model scopes to material cycles has begun for global transport and the transition to electric vehicles (Pulido-Sánchez et al., 2022) and in a global IAM approach (Capellán-Pérez et al., 2020). This research line seems highly relevant for LEMD scenarios. See supplemental information section 4 for a detailed discussion of each study.

(Dafermos et al., 2017) apply the post-Keynesian, Stock-Flow-Consistent (SFC) approach with Georgescu-Roegen's flow fund model to the global economy. Highly innovatively, this model explicitly formalizes monetary and physical stocks and flows, complying with financial accounting rules and the Laws of Thermodynamics. The model encompasses material extraction, recycling, energy use, and GHG emissions in a stylized semi-empirical manner, used in exploratory scenarios. Similarly, (King, 2020) presents a stylized model with monetary and biophysical stock-flow consistency (SFC), implemented in System Dynamics using Input-Output Tables. They consider a finite, regenerating natural resource and energy availability already in their production functions, which indirectly constrains output due to its essential role for capital operation and sustaining the population, as well as labor availability constraints. Data-rich applications of the MEDEAS model built on these principles have been presented for electric vehicles (Pulido-Sánchez et al., 2022) and for a global IAM study (Capellán-Pérez et al., 2020).

3.2 State-of-the-art in Environmentally-Extended Input-Output Analysis LEMD modelling

IO studies usually exogenously impose reductions and shifts in final demand, using the static, demand-driven Leontief production function to model industry's responses. Sectoral granularity is medium to high, depending on the choice of the multi-regional input-output model (MRIO). Economy-wide feedbacks are ignored, e.g., under-utilized capacity, (un)employment, industrial structural change (including industry material stocks), marginal technology adoption. Interactions between sectors and final demand are typically expressed in monetary terms. Rarely physical waste by-products in production are modelled, using hybrid IO technique of 'waste input-output analysis' (Nakamura and Kondo, 2009). However, substantial limitations exist, because statistics on industrial waste by-products and end-of-life waste suffer from considerable quality issues (Tisserant et al., 2017). Hybrid approaches combining MRIO with LCA are used for comprehensive supply chain coverage and detailed process representation, however due to high time and data requirements, this is usually only applied to specific products/industries/technologies. Next steps for EE-IO include better representing secondary materials processing and recycling, improving the robustness of IO tables esp. for the Global South, representing novel technologies and sectors, dynamic modelling of future industrial structures, including production capacity and material stock models; and developing physical IO models (Bruckner et al., 2019; Wieland et al., 2022). These steps will improve material stock-flow consistency beyond price assumptions, and enable linking production explicitly to service provisioning, rather than via monetary final demand alone. See supplemental information section 4 for a detailed discussion of each study.

The reviewed studies start by developing changes to final demand, based on stakeholder workshops on sufficiency

and green consumption (Vita et al., 2019), the SDG target on access to 'all-season' mobility infrastructure (Wenz et al., 2020), hypothetical product light-weighting, lifetime extensions, and improved recycling (Donati et al., 2020; Wiebe et al., 2019), and food waste reductions (Garvey et al., 2021) (Hayashi et al., 2022). Some change the fixed Leontief 'production recipe' (input-output coefficients), while others hold them constant, to model the resulting economy-wide material and energy use as well as GHG emissions. Detailed LCA data is sometimes used to either disaggregate sectors, or translate specific measures into more aggregate sector and final demand categories available in an IO model.

(Gast et al., 2022) conduct a highly innovative global assessment of supply-side industrial symbiosis potentials for steel, cement, paper, and aluminum industries for the year 2017, hybridizing MRIO with MEFA. They find that even major changes to by-product utilization from cement production yields -7% GHG mitigation potentials. If industrial symbiosis is to be promoted, the top priorities are intensified utilization of other cementitious materials and flue gas heat recuperation for electricity generation and heat exchange.

3.3 State-of-the-art in econometric modelling and forecasting

The main strength of this approach is that it does not rely on restrictive assumptions regarding agents and firms' behavior. Three key limitations for LEMD modelling exist: models display high path-dependency and often require complementation with other models. Often simplified stock-flow dynamics are used, depicting materials-oriented measures only through changing demand-price elasticities. Energy use and rebound effects driven by general equilibrium dynamics are often not accounted for, potentially overestimating low demand potentials.

(Pollitt et al., 2020) employ the E3ME model to assess the impact of materials taxation for the carbon-intensive sectors basic metals (steel, aluminum) and cement. They draw on material use rates from MFA (Pauliuk et al., 2016) to estimate sector unit costs and modify input-output coefficients and impose exogenous assumptions about energy intensity. They show that a €80/tCO2 materials tax reduces the EU's energy-related emissions by 6% and process emissions by up to 40%, without carbon leakage, with minimal GDP impacts and slight employment reductions.

(van Ruijven et al., 2016) 2016 rely on carefully selected regression models to build a relatively detailed bottom–up steel and cement model embedded in a long-term global energy system model. They generate future projections of steel and cement demand based on the SSP2 scenario. While they show rapid increases in absence of climate policies, by 2050 steel and cement demand can decrease by 80–90% and 40–80% below 2010 level if a carbon tax of 100 $/tCO$_2$ + 4%pa is imposed. Yet, availability of CCS plays a major role.

(de Souza and Pacca, 2023) evaluate the CO2 mitigation potential of circular economy strategies considering jointly the cement and steel industries in Brazil: recycled-based EAF and charcoal-fired BF in the cement industry; material efficiency, the substitution of supplementary cementitious materials for clinker and the substitution of petroleum coke with alternative fuels. They show that together, circular practices and industrial symbiosis can avoid 52% of the business-as-usual emissions up to 2050 at US$ 10/tCO2e.

A highly innovative and notable effort not yet addressing material cycles explicitly is the MARCO-UK model, first energy-economy-wide model to include thermodynamic (energy) efficiency, and the useful stage of energy consumption (as useful exergy). For example, (Sakai et al., 2019) use MARCO-UK and show that around a quarter of historical UK economic growth since 1970 could be attributed to gains in economy-wide thermodynamic energy efficiency.

3.4 State-of-the-art in equilibrium-based macro-economic LEMD modelling

This tradition usually models lower demand only compared to a growth-oriented business-as-usual scenario; see supplemental information section 4 for a detailed discussion. Most do not find actual absolute LEMD reductions, which is often confusingly communicated by mainly reporting modelled 'reductions' vis a vis a questionable growth BAU scenarios. In the simplest form, elasticities for materials-producing and using sectors are modified exogenously (Zhang et al. 2022). More innovatively, models are extended with the production of specific materials or raw material extraction, however without biophysical consistency across material cycles and stocks (Nong et al., 2023; OECD, 2019; Schandl et al., 2020). Those studies report that even highly ambitious, supply-side resource efficiency and climate change mitigation measures result in a +50-100% increase of global resource use, driving further ecological deterioration. Interestingly, (Nong et al., 2023) nest Leontief production functions into widely used CES functions by introducing 'technology bundles' for three key industries—steel manufacturing, land transportation, and electricity generation, consisting of various technologies using distinct combinations of inputs, capturing practical constraints in substituting labor and capital between technologies, at least in the short-term. Material stocks and service provisioning are usually not included in non-monetary units, except when combined with an explicit material stock turnover model from the MEFA tradition (Cao et al., 2019). They assume perfect factor allocation, full capacity utilization and rational agents ('homo oeconomicus'), which is questionable, esp. because LEMD probably results in under-utilized capacities, dis-equilibrium due to oversupply, e.g., fossil fuels and products using them, as well as early decommissioning of stranded assets. Widely used CES industrial production functions assuming full substitutability of energy violate thermodynamics, ignoring that final energy/exergy are complements in industrial production (Keen, 2021; Keen et al., 2019; Stern, 2011). Introducing full thermodynamic consistency for material cycles, energy use, material stocks, as well as extending service provisioning beyond monetary valuation are required.

CGEs can also be combined with dynamic MEFA to explicitly and biophysically model stock-flow dynamics. (Cao et al., 2019) combine a CGE model with a dynamic MEFA for residential buildings in China, considering service and stock saturation (m^2 per capita). Modelled construction material use feed into their CGE model to quantify economy-wide effects, ensuring both biophysical and monetary consistency. Exogenously assumed lower building service saturation levels and delayed stock development could save 25.4 Gt in embodied CO2 emissions in the construction sector, partially offset by economy-wide rebound effects of 18.8 Gt, assuming GDP remains constant and is re-distributed to other sectors. (Tong et al., 2022) investigate global shifts from internal combustion engines to battery electric and fuel cell vehicles, covering supply and demand for platinum group metals and GHG emissions, combining the IMED CGE with a dynamic MEFA for cars. They model several scenarios for future car stock saturation levels, structured via Multi-Level Transitions Theory. They highlight potential future mismatches between platinum group metals extraction, vehicle production, and end-of-life vehicles for recycling.

Highly innovatively, (Bachner et al., 2021) extend a CGE by explicitly modeling service demand using non-monetary indicators, construct an alternative wellbeing indicator, and quantify co-benefits and avoided burdens, for Austria. They model measures avoiding, shifting and improving demand for buildings and transport. They use an energy-focused building vintage model (m^2 of floor area), and represent transport modes and travelled distances, which are later converted to monetary units via stock-flow-service relations. Their alternative wellbeing indicator covers monetary welfare effects for private and public consumption, co-benefits such as avoided air pollution incl

health impacts, and changes in leisure. In their ambitious climate transformation scenario, they find GDP to decline slightly, while societal welfare increases.

3.5 State-of-the-art in partial equilibrium LEMD modelling

PE sector models are technology-rich optimization models built on thermodynamic consistency for their respective sector, with exogenous demand either from GDP, population or specific material/energy demand dynamics using econometric methods, and often assumed automatic material and energy efficiency gains. PE models are increasingly combined with models from other traditions, especially for modelling demand for energy services, which has been presented at high granularity using physical service provisioning indicators (Gaur et al., 2022). PE often draws on data from other traditions, such as LCA, engineering, or industrial ecology, requiring complex and time-intensive data harmonization. Usually, there are little considerations of rebound effects (van den Berg et al., 2019). Future decoupling of economic growth from energy and material needs to be exogenously assumed. It is so far unclear, if a high level of detail for consistent service and material demand in PE IAMs is feasible, or if soft-coupling with other models or innovative multi-model analysis like e.g., applied in (Gaspard et al., 2023) is more advantageous. See supplemental information section 4 for a detailed discussion of each study.

(Grubler et al., 2018a) present the groundbreaking Low Energy Demand (LED) scenario, covering service provisioning not only for energy services but for thermal comfort, consumer goods, mobility, food, commercial and public buildings, as well as upstream freight transport and industry activities, quantified at the global level via the hybrid MESSAGEix-GLOBIOM model. The scenario combines reduced energy and material demand with substantially increased supply chain and end-use service provisioning efficiency, finding that final energy demand could decrease by - 40% until 2050. Focusing on one country, (Barrett et al., 2022) report a reduction of -52% in energy demand by 2050 compared to 2020 in the UK, resulting from technical and behavioral measures without compromising wellbeing. To consistently represent all services, they enrich the macro-economic model TIMES using an MRIO, apply dynamic MEFA for construction, buildings and the food industry, and a bottom-up transport model. In this 'whole-systems' model, industry interacts with transport services, construction, building stocks and their lifecycle, and nutritional requirements, as well as endogenous economic growth. A high level of detail for options to 'improve' energy efficiency, 'avoid' energy use and 'shift' to more efficient energy demand provision can be covered. Also modelling lower energy service demand for one country, (Oshiro et al., 2021) find a potential of -37% reduction in final energy demand by 2050 for Japan. They apply the technology-rich PE energy systems model AIM/Enduse for Japan, which is exogenously driven by GDP and population and as their industry sector is not linked to final demand, dematerialization and material efficiency factors (elasticities) are exogenously modified and no material cycles or stocks are depicted.

There are attempts to extend PE IAM models for an improved material representation either focusing on specific sectors like steel and iron (Zhang et al., 2019), food (Springmann et al., 2018), forests (Daigneault et al. 2022) or materials like plastics (Stegmann et al., 2022) or on specific measures like e.g., a global transition to autonomous shared vehicles quantifying operational and industrial energy use, basic materials (cement, iron/steel, plastics) and GHG emissions (Akimoto et al., 2022). There are also attempts to incorporate ores and metal extraction and processing sectors, typically absent in PE models, incorporating material availability constraints over time, addressing measures such as technology lifetime extension, recycling, and material intensity reduction (Tokimatsu et al., 2018). They find that metal requirements vary significantly across scenarios and uncertainties, with some metals, including Vanadium, consistently deemed critical. Combining dynamic MEFA with a PE leads to stock-flow consistency, which increases the credibility for medium- to long-term projections of structural change and

material availability, in particular. (Kermeli et al., 2022) find steel demand for 2100 to be -75% lower than in flow-based estimations when explicitly modeling steel stock-flow dynamics, incl. end-of-life recycling and assumed per capita saturation of stocks. (Lechtenböhmer et al., 2015) assess how re-industrialization and energy-intensive industries can be aligned with the German Climate Protection Law. The study employs a technology-rich energy systems PE model and a simplified stock-flow MEFA model. Re-industrialization could impede Germany's energy and GHG targets due to limited efficiency potentials, requiring further demand-side measures. (Deetman et al., 2021, 2020, 2018) combine an IAM with dynamic stock-flow MEFA endogenously modeling global material requirements for electricity, buildings, vehicles and appliances under climate policy scenarios. Innovatively, this approach provides biophysical consistency between the demand for service provisioning, material cycles and stocks, including repercussions for industry.

Two multi-model studies driving PE energy system models with exogenously driven demand from other modules and/or demand-side measures are also identified. (Costa et al., 2021a) soft-couple PE, LCA, MEFA and MRIO modelling to assess European net-zero pathways. They find that behavioral changes could contribute -20% of the GHG reductions needed for net-zero by 2050. (Günther et al., 2019) combine resource efficiency and demand-side measures to model net-zero pathways for Germany. They present a technology-rich multi-model analysis driven by exogenous assumptions for sub-modules for transport, heating and cooling in buildings, agriculture and forestry, which then drive a PE energy optimization model, a waste module, and a global trade model. The most ambitious scenario combining phase-outs, supply-side efficiency and technological progress with demand-side measures shows that until 2050, GHG emissions can be reduced by -95%, raw material consumption by -56% and final energy consumption by -24%.

3.6. State-of-the-art in System Dynamics LEMD modelling

We find several studies integrating environmental, biophysical, economic and social considerations. System Dynamics models simulate dynamic interlinkages between multiple evolving parts of a system. The complexity and traceability of models limits system expansion, their simulation approaches are validated on historical relationships, and the structures of the models can limit which scenarios can be modeled, or would require exogenously overruling parts of the dynamic system. More systematic coverage of material cycles, stocks and esp. service provisioning could make this tradition highly interesting for LEMD scenarios. See supplemental information section 4 for a detailed discussion of each study.

(Allen et al., 2019) simulate supply- and demand-side measures for Australia, incl. economy-wide raw material extraction, final energy, and selected material stocks. Their 'Sustainability Transition' scenario achieves 70% progress towards the SDGs by 2030, while focusing either on economic growth, social inclusion, or green economy strategies achieves limited progress. (Moallemi et al., 2022) model low-demand pathways to achieve the SDGs, depicting service provisioning and socioeconomic wellbeing via a capability's perspective, and use life expectancy and the Human Development Index as headline indicators. Industry and the economy are only represented via aggregate Cobb-Douglas production functions. They find that multiple early interventions are necessary to facilitate long-term SDG progress after 2030. (Neumann and Hirschnitz-Garbers, 2022) quantify how a 100% renewable energy system globally impacts material reserves and utilization of bulk- and precious metals. They find that improved recycling can reduce potential economic constraints due to the depletion of high-grade raw material reserves. (Sverdrup and Olafsdottir, 2023) extend the World7 IAM with complete cement, sand and metal cycles, incl. energy use and GHG emissions, complying with mass and energy balance. Their low-demand scenario

assumes a global stabilization and then decline of concrete stocks per capita, low carbon energy and industrial processes, as well as improved recycling and material substitution.

(Kumar et al., 2021) present a noteworthy and innovative model of the energy and materials required to achieve development goals in India, e.g., food and water security, housing and clean energy for all, sufficient healthcare and access to clean cooking and transport. Sectoral growth is also driven by a soft-linked CGE model to ensure macro-economic consistency. Highly innovatively, they explore how urban built form shapes housing and transportation resource and energy demand.

3.7. State-of-the-art in Life Cycle Assessment LEMD modelling

Using detailed LCA for system-level modelling and LEMD scenario analysis requires methodological advancements and models from other traditions to overcome typical limitations, especially of attributional LCA. Recent advances include consequential LCA, as well as upscaling through combining LCA with dynamic MEFA and its stock-flow models. See supplemental information section 4 for a detailed discussion of each study.

(Verhoef et al., 2018) estimate the energy savings potential of additive manufacturing across multiple sectors using attributional LCA, and find substantial technical energy saving potentials, not considering rebounds nor shifts in demand. (Van der Voet et al., 2019) combine consequential LCA with a stock turnover model to assess metals production and recycling for future energy scenarios. They find that increasing secondary metals use could reduce life-cycle emissions substantially at the global level, but only in the second half of the 21st century when end-of-life metals increasingly become available from ageing material stocks. (Buschbeck and Pauliuk, 2022) use consequential LCA to assess when substituting emission-intensive materials with timber leads to net GHG savings, considering that growing forests are also natural carbon sinks. They find that short term (<25 years), intensive wood harvest is not climate beneficial, while long-term potentials depend on the speed of energy system- and industrial decarbonization.

An important contribution to LEMD futures is the modelling of the required resources and emissions for sufficient consumption, 'just' access to basic services, and DLS, using LCA. (Bjørn et al., 2018) use a hybrid of attributional LCA and MRIO to estimate the climate impact of surveyed household consumption baskets for ten service demand areas in Denmark, finding required reductions of supply- and demand-side emission intensities by factor 2-14 to comply with climate targets. (Rammelt et al., 2022) estimate life-cycle impacts of 'just access' to energy, water, food, housing and transport drawn from SDG indicators globally, and eclectically combine attributional static LCA factors. In 2018, eradicating severe deprivations could amount to 2–26% additional impacts on climate, water, land, and nutrients, amounting to similar impacts induced by the wealthiest 1-4%.

Recently, research on DLS has proliferated, with studies addressing a common set of products and services required for Decent Living, including housing, mobility, and nutrition, for some Global South countries (Mastrucci et al., 2020; Mastrucci and Rao, 2019; Rao et al., 2019) and globally (Jarmo S. Kikstra et al., 2021; Millward-Hopkins et al., 2020). Detailed LCA inventories for the DLS dimensions are directly linked to the use of materials and stocks by households, MRIO-based footprints address truncation errors and dimensions where the linkage with materials is less clear (nutrition, education, healthcare, and socialization), and IAMs such as MESSAGEix-GLOBIOM can be used to estimate impacts from energy supply and decarbonization. Food and transport dominate energy for decent living, while housing dominates upfront energy investment needs; in sum, 149-156 EJ/year of final energy would be needed after 2040, ~60% less than today (Jarmo S. Kikstra et al., 2021; Millward-Hopkins et al., 2020). Nutrition and mobility at DLS globally would require 6 t/cap tons of raw materials, and stocks of ~43 t/cap in

buildings, infrastructure and industrial assets (Vélez-Henao and Pauliuk, 2023).

3.8 State-of-the-art in dynamic Material and Energy Flow Analysis LEMD modelling

Dynamic MEFA focuses on a thermodynamically consistent representation of material cycles and material stocks at national to global scales, either for sectors or materials, usually treating socio-economic dynamics as exogenous. A rapidly growing number of studies investigates how lower demand for material product stocks is a crucial demand-side measure, which combined with material efficiency, circular economy strategies, technological improvements in industry and energy system decarbonization can achieve 1.5-2°C compatible pathways. For this purpose, dynamic stock-flow modelling is often combined with energy statistics, LCA and EE-IO to model supply chain energy use and GHG emissions. First combinations with macro-economic models are also identified. See supplemental information section 4 for a detailed discussion of each study.

A common approach is to study the technical potential of reducing turnover across the entire material cycle, by combining possible technical changes in all process steps, including manufacturing (light-weighting and less scrap), longer and more intensive use, and better re-use and recycling (Ciacci et al., 2020; Kalt et al., 2022; Pauliuk et al., 2021; Song et al., 2023; Wang et al., 2022; Watari et al., 2022; Zhang et al., 2018). In those studies, material cycles and stocks are linked to energy use and GHG emissions, enabling thermodynamically consistent modelling of GHG mitigation potentials from materials-oriented strategies. As (Krausmann et al., 2020) show for 2015, ~40% of global energy use and GHG emissions were required by industry, transport and construction for stock-building, and ~60% for stock utilization and service provision.

In addition, it is common to exogenously assume lower stock growth or lower stock saturation levels in the future, which inevitably leads to lower material and energy demand, although with substantial delays (Zhou et al., 2022) (Watari et al., 2022) (Watari et al., 2020; Watari and Yokoi, 2021) (Krausmann et al., 2020) (Cao et al., 2020) (Cao et al., 2021) (Pauliuk et al., 2021; Zhong et al., 2021) (Kalt et al., 2021) (Ciacci et al., 2020). Saturated/stabilized material stocks, combined with longer lifetimes and high recycling would drive substantial reductions of raw material extraction and subsequent energy use. The socio-economic feasibility of lower in-use stocks is, however, assumed and not endogenously modelled nor explained. These scenarios therefore show the extent to which demand-side reductions would be needed to comply with global climate targets, under realistic supply-side improvements and industry decarbonisation pathways.

Dynamic MEFAs are also used to model land-use and the industries extracting and processing biomass for food, feed, biofuels, material use and as potential carbon sinks. (Mayer et al., 2022) model the European food and land-use system, combining dynamic MFA and consequential LCA. Several low demand scenarios explore alternative diets and variable non-food product demand for biofuels and material use. They find that agroecology can mitigate some emissions, but only if combined with less meat consumption, a smaller-sized agri-food system, and if livestock systems are better aligned with regional feed production capacities. (Bailis et al., 2015) quantify the carbon emissions due to pan-tropical woodfuel supply and demand for subsistence cooking and commercial uses, using spatially-explicit information on supply, travel distances and demand. They find that 27-34% of woodfuel harvested exceeds annual biomass regrowth, resulting in ~2% of global and ~4% of pan-tropical GHG emissions. (Le Noë et al., 2021) analyze timber harvest and natural carbon stocks in forests from 1990-2020, using an ecologically-informed dynamic MFA for global forests. They find that if harvest had not increased since 1990, forests could have stored 4.9 Gt of additional carbon. A “no harvest” scenario would have increased biomass carbon

stocks by 49.1 Gt, showing substantial mitigation potentials of lower wood use.

3.9. State-of-the-art in Agent-Based LEMD modelling

ABMs enable detailed representation of (inter)actions of heterogenous agents resulting in emergent non-linear dynamics, hence they can assess distributional aspects, diffusion and uptake of innovations, or shocks and climate damages (Lamperti et al., 2019, 2018) Many studies build on Post-Keynesian theory and evolutionary economics, or derive agent behavior from qualitative research and transdisciplinary co-production. Focusing on agent's decision-making necessitates granular data, which so far results in less emphasis on industrial transformation, as well as data-rich scenarios for material cycles, stocks and energy use. At the national to global levels, ABMs resemble System Dynamics models, as only aggregate agents are considered. For LEMD scenarios, this tradition could be highly useful to model social dynamics and the diffusion of innovations beyond rational optimizers. Given the transdisciplinary, participatory potential to co-develop models and scenarios, this tradition could also be a useful to co-develop locally/regionally grounded LEMD pathways and service provisioning demand together with communities and stakeholders. (Safarzyńska and van den Bergh, 2022) study the impact of unemployment and inequalities on the social cost of carbon. (Yazan and Fraccascia, 2020) and (Koide et al., 2023) present concepts for building data-rich scenarios exploring how a more circular industrial system could be implemented at the household and the firm levels, including consumer and supplier decision-making in response to repairing and refurbishing.

3.10 Quantitative evidence synthesis of mitigation potentials

The reviewed literature finds substantial potentials for reducing material and energy demand, as well as mitigating GHG emissions (Figure 3). For material use, we find reduction potentials from -1 to -80% when considering all study scopes (Figure 3a). Economy-wide reduction potentials of combined supply- and demand-side measures were reported at 56% when compared to historical base year (i.e. last data-driven year), and 2-47% compared to BAU scenarios (i.e. last year of future scenario). The most effective single measure with a -52% reduction of material footprints compared to 2020 is a scenario of global contraction and convergence to DLS (Vélez-Henao and Pauliuk, 2023). For individual sectors, reductions of up to -63% of phosphorous fertilizer in food systems through a combination of technological and diet change (Springmann et al., 2018) and up to -80% reduction of steel demand through LED-type transformations combining supply and demand-side measures (Oshiro et al., 2021) were reported for annual use in 2050 compared to BAU scenario.

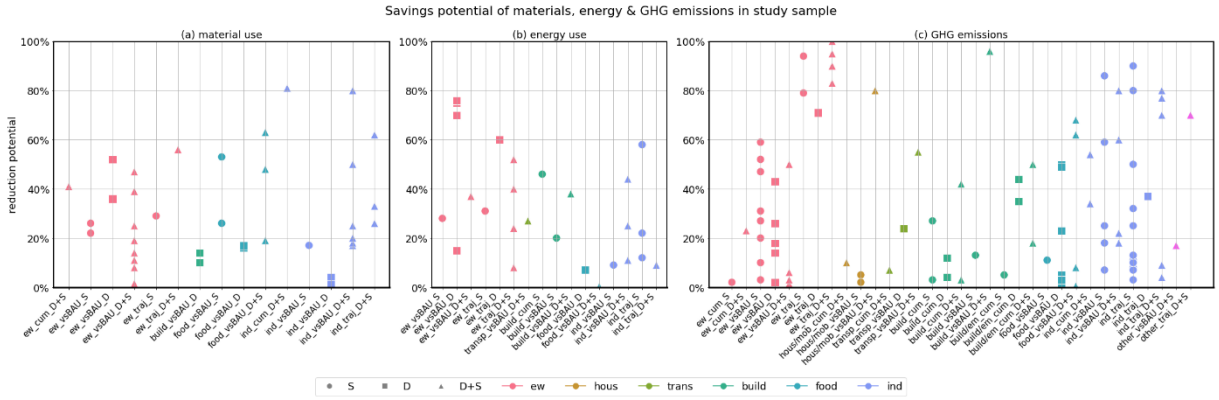

Figure 3: Summary of savings potentials for material and energy use, as well as GHG emissions across all relevant studies, grouped by sectoral and temporal scope, as well as supply-side (S), demand-side (D) and combined supply- and demand-side (D+S) measures. ew = economy-wide, hous/mob= housing & mobility, build = buildings, build/em = buildings embodied flows, food = agriculture & food, ind = industry; cum = cumulative, traj = trajectory from historical base year to scenario year, vsBAU = comparison of annual reduction to business-as-usual scenario). Please note that the exact time and sectoral scopes, as well as mitigation measures within categories might still differ (e.g., some studies accounting cumulative emissions from 2010-30 vs. 2010-50, or industry reduction potentials including estimates for different materials industries like steel, copper, etc.). Due to the comparison to either the historical base year, or a base scenario, values can still be compared. For a detailed account of scopes, we refer to SIX.

For energy use, we find reduction potentials of -0.3 to -76%, when considering all study scopes (Figure 3b). The strongest economy-wide reduction potential of up to -76% in 2050 annual global energy demand was reported for demand reductions to DLS (Jarmo S Kikstra et al., 2021), representing a ~60% reduction when compared to historical base years (Millward-Hopkins et al., 2020). These are followed by LED-type transformations combining supply- and demand-side measures with reduction potentials between 40-52% compared to historical base years (Barrett et al., 2022; Gaur et al., 2022; Grubler et al., 2018a). For buildings, we find material substitution to reduce cumulative energy use from 2020-50 in India by -46% (Kumar et al., 2021). For industry, we find global energy use for steel and cement production reduced by -22% and -58% though a carbon tax of 20-100$/tCO2 respectively (van Ruijven et al., 2016).

For GHG emissions we find reduction potentials from -1 to -100% when considering all study scopes (Figure 3c). Economy-wide emission reductions between -70% and -100% (i.e. net-zero emissions) are achieved in several studies through combined demand and supply-side measures (Barrett et al., 2022; Costa et al., 2021b; Gaur et al., 2022; Günther et al., 2019; Moallemi et al., 2022). Obviously, the decarbonization of the energy system plays a large role for reducing GHG emissions. Large reductions of economy-wide emissions of individual measures were reported for 3D printing (-27% annual), remote work and active travel (-26%), demand-reduction (-23% cumulative), local/sharing service economy (-18%) and vegan diets (-14%). For additional insights on sectoral potential, please consult the supplemental information section 3.

4. Discussion

4.1 Sector definitions, system boundaries, and modelling principles to depict industrial networks

We identify the below entry points to model the biophysical basis of LEMD scenarios in the reviewed literature, suggesting the need for a unified system definition and shared modelling principles to enable comparability, leverage model combinations, knowledge accumulation and facilitate evidence synthesis.

UNFCC emissions accounting defines the following broad economic sectors: energy supply, industry, agriculture and forestry and other land use (AFOLU), transport, and buildings (Lamb et al., 2021; IPCC, 2022). This "end-of-pipe" perspective on the 'sources' of emissions lacks a differentiation of supply and (final) demand and separates interconnected sectors, which jointly respond to demand by forming an industrial network. Depending on statistical practices across countries, extractive industries are variously allocated across energy supply, industry, construction and AFOLU, hindering systematic analysis of material cycles and energy use.

Energy statistics provide detailed information on supply and use of energy carriers for sectors, production processes and final demand, and distinguish between primary, final, and useful energy stages. Leveraging this information is highly relevant for LEMD modelling, to understand potentials and limits of fuel switching, electrification and energy efficiency (Cullen and Allwood, 2010; Sakai et al., 2019).

Raw material extraction and land use, which constitutes the 'start' of material cycles, is reported along boundaries established in the System of Environmental-Economic Accounting (SEEA) and focuses on types of raw materials, e.g., biomass, non-metallic minerals, ores and metals, as well as fossil energy carriers, lacking inherent sector resolution (Krausmann et al., 2017). This data is increasingly used across traditions, requiring modelers to compile data on material cycles and waste by-products occurring at each production step, linkage to input-output tables for sector resolution, as well as differentiation into final products accumulating as stocks (Plank et al. 2022; Streeck et al. 2023a,b). Industry production statistics, such as those for cement or steel, focus on specific stages of the value chain and material cycle, often used eclectically for selective coupling into models.

Waste statistics, if available at all (Tisserant et al., 2017) (United Nations Environment Programme and International Waste Management Association, 2015), cover only what is officially collected and managed in institutionalized waste management systems, leaving large unknowns. Systematic use requires time-intensive mass-balancing and harmonization to quantify the end-of-life part of material cycles. Some models therefore resort to estimating waste flows as a function of GDP or population, violating thermodynamics i.e. mass-balanced consistency with material extraction, industrial processing, and material stock dynamics.

To model material cycles for LEMD scenarios, we suggest an economy-wide system definition for industry following the SEEA[2] framework which covers extractive sectors and basic industries (agriculture, forestry, mining, refining, processing), manufacturing, construction, energy supply to industries and to final demand, as well as service sectors (transport services, health, financial sectors, etc.), and repair, recycling and waste management sectors. LEMD modelling could be substantially advanced via a consistent depiction of the industrial system regarding physical and monetary layers, supply and demand, interactions between industries, as well as stock vs.

[2] The SEEA draws on economy-wide material flow accounting for raw material extraction, energy statistics for sectoral energy use, as well as UNFCC emissions reporting (Krausmann et al., 2017; OECD, 2008) into a (relatively) coherent framework integrating economic, social and environmental information (UN, EU, FAO, IMF, OECD, WB, 2014), however not reporting full material cycles yet.

flows, at least enabling a clear documentation of any specific model scope to facilitate comparability (Figure 5). Ideally, LEMD scenarios are based on a consistent model of material cycles, from extractive industries to industrial assets and infrastructure to the waste management and circular industries, which is essential for delineating and capturing the implications for energy use and emissions.

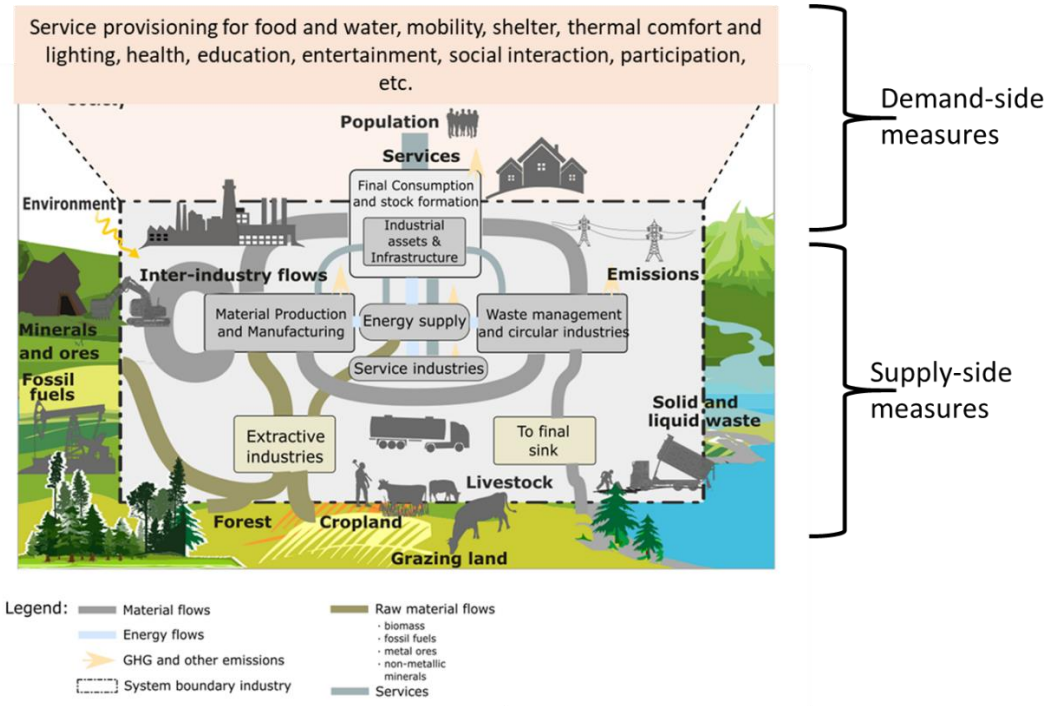

Figure 5: Conceptualizing socio-economic material cycles, energy use, economic sectors and service provisioning, drawing on (Chen and Graedel, 2015; Haberl et al., 2019; Kalt et al., 2019).

4.2 Modelling industrial production for LEMD modelling

LEMD modelling of industrial networks needs to depict how supply reacts to changes in demand and service provisioning. At the level of the industrial sector, so-called 'production functions' model the input of labor, capital, energy, and materials in response to intermediate and final demand for each sector's output. A shared understanding and use of appropriate production functions that are consistent across aggregation levels is crucial for LEMD modelling (Keen et al., 2019; Pauliuk et al., 2017; Stern, 2011) (see supplemental information section 6). For a consistent description of material and energy flows and stocks, the mass und energy balance of industrial sectors needs to be respected, which includes a proper accounting of by-products, waste, and emissions. Engineering limits to efficiency need to be respected by the different modelling traditions to prevent the inclusion of unrealistic or even infeasible efficiency gains, including aggregate decoupling of economic growth from energy and materials. Production models should discern different quality grades of energy, such as primary vs. final energy/exergy or high, medium and low temperature heat as well as the different material quality grades required for production. Production functions should allow for varying or incomplete capacity utilization, a common phenomenon in LEMD futures. An option to include more realism in production modelling is to split inputs into fixed inputs that scale with capacity and operating input that scale with the output.

While production functions model individual sectors, models of markets and market mechanisms are needed to determine the market share of different suppliers. A crucial feature of interdisciplinary LEMD industry modelling is to explicitly consider market mechanisms not only for the industrial commodities but also for production factors labor and capital as well as materials and energy carriers. Here, market models from the different disciplines can be combined to accurately reflect the nature of individual markets (equilibrium, disequilibrium, controlled or free).

4.3 Service provisioning and demand modelling

Demand-side LEMD transformation options become visible when making the relations between human wellbeing, service provisioning, product stocks, industry and environmental impacts explicit and assessing decoupling potentials at each step of the so-called Energy Service Cascade[3] (Fig. 5). The reviewed literature predominantly focuses on the demand for shelter, mobility, nutrition and thermal comfort, and less on sectors like health, education and leisure activities (Figure 2). What is actually modelled in most studies are product stocks such as the number of appliances, or weight of buildings (per capita), as well as functions provided by stocks and energy use, such as square meter of well-tempered living space. Service provisioning of 'what is actually demanded' is usually done via exogenously imposed levels of functions, either derived from policy targets, trans-disciplinary deliberations aiming at political legitimacy, or via the researcher's choices.

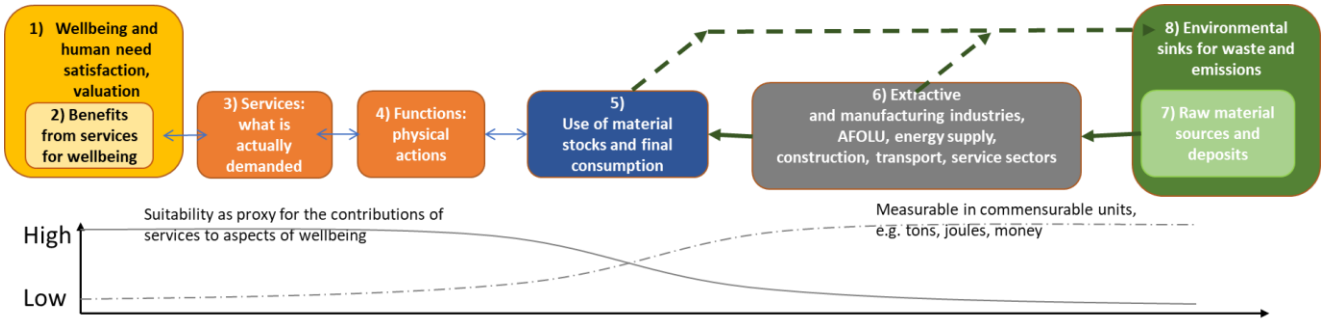

Figure 4: Relations of wellbeing, human needs, to service provisioning, material stocks and economic production, drawing on natural resources, resulting waste and emissions. Adapted from (Kalt et al., 2019).

In the reviewed literature, we find three approaches to modelling demand in general and for service provisioning specifically, via 'consumption functions', which expresses how a basket of goods and services is chosen under constraints. This requires a choice of commensurable units, as well as theoretical assumptions about how actors decide among competing alternatives. First, optimization which is widely used in macro-economic traditions uses variations of (bounded) rational choice theory and monetary valuation, assuming maximization of 'utility' (consumption). Expanding the notion of utility to leisure, unpaid care work, quality of life and wellbeing, as well as non-monetary values seems necessary. Second, exogenously given policy-relevant targets, or extrapolations based on observed economic dynamics are also used, providing useful what-if insights, however often lacking

[3] As Virág et al. (2022) demonstrate for mobility, more distances travelled don't translate into a better service ('being able to reach places'), or higher wellbeing contributions, and a more explicit representation of the link between human wellbeing, needs satisfaction, the required product functioning and in-use stocks is needed to better understand decoupling potentials on the social side. Such research on low demand scenarios the stock-flow-service-wellbeing nexus is only in its infancy.

behavioral foundations about who, how and why. Third, policy measures as well as future consumption baskets developed via transdisciplinary co-creation efforts, such as in citizen assemblies or stakeholder workshops, are highly innovative and promising to achieve transformative impacts and insights.

4.4. A roadmap for improved LEMD scenario modelling

We summarize our insights as eight recommendations for future LEMD modeling to contribute more nuanced, biophysically consistent, and policy-relevant scenarios and insights for climate change mitigation and sustainability. For an extended discussion, see supplemental information section 7.

Interdisciplinary combinations of modelling principles and traditions yield more robust, nuanced and policy-relevant insights than any single tradition alone can provide. Combining models requires carefully considering and potentially harmonizing differences in system definitions and modelling principles (see section 5.1.). Collaborating with the social sciences helps to understand how demand and service provisioning are organized, what acceptable and just low-demand futures could be like, and how they might be achieved.

Thermodynamic and Biophysical Consistency: To capture economy-wide and time-dependent implications of LEMD scenarios, it's crucial to achieve consistency across material cycles, material stocks, energy use, by-products and waste, and emissions. Ideally, this is achieved at high granularity, spanning from primary extractive sectors, industry and manufacturing, final consumption, recycling, and waste management, to service provisioning. Ideally, economic, biophysical, and social data layers are consistently integrated, complying with their respective rules of consistency.

Stock-Flow-Service Nexus: The efficiency of transforming material and energy into services hinges on existing material stocks in products, buildings, and infrastructure. Ideally, these relations are consistently represented in models. The SDGs and other policy targets are useful starting points. Transdisciplinary co-creation approaches can be useful to develop context-specific "low-demand" scenarios. Non-monetary service provisioning indicators improve our understanding of the links between wellbeing, human needs, and service provisioning systems.

Wider Spectrum of Supply and Demand-Side Measures: Enlarging the solution space is necessary to develop net-zero compliant LEMD pathways, which might result in dis-equilibrium, stranded assets, and early decommissioning. This includes standard economic instruments, as well as regulatory measures, product standards, institutional changes, government activities, financial markets, changes in settlement patterns and urban forms, as well as socio-behavioral dynamics.

Assess Telecoupling in Global Supply Chains: Modeling global supply chain interactions is critical to identify potential rebound effects and burden-shifting, as well as economic winners and losers in LEMD transformations. The different layers of industrial assets (capacity, capital, material stocks), as well as the different stages in supply chains (resource extraction, material production, manufacturing, waste management, recycling, energy supply and service sectors) should therefore be explicitly represented, to understand capital constraints for LEMD scenarios and potential global re-allocations of capital, labour, and natural resources, as well as their transport implications, across global supply chains.

Resource Constraints, Vulnerability, and Resilience: Modelling should address the complex socio-ecological dynamics, feedbacks, and non-linearities inherent in LEMD transformations and the biosphere. The environment is more than a repository of resources to be extracted and a sink for waste and emissions. Complex trade-offs exist between different environmental aspects, ranging from the climate and biodiversity crisis to other Planetary Boundaries. Some of the reviewed models can address some of these concerns (see supplemental information

section XX). Ideally, the social implications of deep structural changes as well as societal crisis for labour, incomes, skills, and inequality are also assessed.

Improved Research Infrastructure, Open Science and Community Standards: Findable, Accessible, Interoperable, and Reusable (FAiR) research findings and models are crucial for cumulative research and evidence synthesis (Hertwich et al., 2018; Pauliuk, 2020; Wilkinson et al., 2016). Ongoing community efforts, for example by the Integrated Assessment Modeling Consortium[4] (IAMC), the International Transport Energy Modeling (iTEM) network[5], and the Energy Demand changes Induced by Technological and Social innovations (EDITS) network[6] aim to diversify and broaden contributions to the 7th IPCC assessment cycle and beyond. We recommend that LEMD modelers consider the data reporting requirements of such assessments early on in their model development, ideally developing a shared ontology across traditions and models, to facilitate comparability and evidence synthesis.

Connecting to the updated Shared Socioeconomic Pathways (SSPs) is timely, so that LEMD scenarios can readily contribute to evidence synthesis and global assessments reports. The SSPs are a common framework connecting research on mitigation, adaptation, and impacts. Since their inception in 2014 they have been developed further (Green et al., 2022; van Ruijven et al., 2022), with substantial quantitative updates[7] to be released in 2024. More fundamental revisions are also being discussed. Ideally, future LEMD modeling takes up the most recent SSP version and contributes to ongoing discussions about a new low-growth/low-demand SSP. Explicitly quantifying service provision levels in the SSPs is essential for comparability across LEMD models. Additionally, a significant challenge for new entrants in IPCC scenario submissions is ensuring their models generate sufficiently consistent data for comparison with larger-scale models, while maintaining sectoral or national specificity.

5. Conclusions

We assessed the findings and underlying models of 77 state-of-the-art studies originating from nine modelling traditions published between 2014-2023, which explore Low Energy and Material Demand (LEMD) futures. Interdisciplinary combinations of modelling traditions are on the rise, leveraging their respective strengths for more nuanced and robust insights. We do find large mitigation potentials for materials, energy and GHG emissions across studies, given substantial challenges in extracting, harmonizing, and synthesizing findings. We recommend the development of shared concepts and ontologies, as well as widespread adoption of open science and FaiR data principles, to facilitate comparability as well as systematic and robust evidence synthesis.

We find that service provisioning and demand are increasingly represented via non-monetary indicators for end-use products and the physical actions they provide. An important next step is to assess how much is sufficient for decent living and wellbeing, to develop justified and acceptable scenarios across different contexts. Few models fully link material cycles, material stocks, energy use, waste and emissions in a thermodynamically consistent manner. Those who do are rather coarse in their representation of socio-economic interdependencies and dynamics driving changes. Models with comparatively better representation of socio-economic complexity and dynamics often do not fully comply with thermodynamic principles. In summary, the reviewed models seem to be either too aggregate, or too specific. When considering the multiple properties which are important for modeling industry

[4] https://www.iamconsortium.org
[5] https://transportenergy.org/
[6] https://iiasa.ac.at/projects/edits
[7] https://depts.washington.edu/iconics/, https://www.iamconsortium.org/event/iconics-and-iamc-joint-webinar-shared-socioeconomic-pathways-ssps-update/

transformation (detailed physical and economic representation of industrial assets and production flows, detailed representation of the political and legal framework and form behavior given these circumstances, etc.) comprehensiveness at sufficient detail is a criterion hardly achieved.

To improve LEMD modelling, we herein propose a general comprehensive system definition and eight suggestions for future work. A question for further exploration is how the required comprehensiveness and granularity can be achieved in a resource-efficient way, so that real life decisions can be robustly informed.

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Electricity Consumption in the Italian Retail Electricity Market

Contribution to the EDITS project: Quantification of the residential energy demand repercussions of the energy crisis in Europe and associated energy price shocks, based on high-frequency smart-meter electricity data for Italy

Matteo Muntoni (CMCC)

1. Introduction

This study explores the impact of electricity pricing on electricity consumption measured through smart meters, using a unique dataset of italian households. The objective of the study is to assess how changes in price influence user behavior and we calculate the price elasticity of household level demand both in the short and the medium term.

For this study, we use hourly electricity consumption data from smart meters provided by a large Italian utility company over a period of more than 2 years between January 2020 and March 2023. Starting from data for all the households' electricity contracts of the utility in the Italian domestic electricity market that were associated with a smart meter (latest technology with hourly metering) in June 2022, we selected an appropriate sub-sample for our analyses following some criteria. We also exploit contractual information to analyse a possible differential behavior to price change for households with variable and fixed-price contracts.

Our final sample consists of 20,422 contracts, some with fixed and some with variable-price contracts.

In this study, we are not interested in estimating the effect of prices on the electricity contracts' choice, which is anyway a relevant research question. Instead, we are interested in isolating the direct effect of prices on electricity consumption, and we exploit supply-side variations while keeping constant our ob- served demand side. We estimate the price elasticity of demand given that our demand is made of electricity contracts that have been chosen ex-ante and that have not been changed. As a result, our sample consists of households who made the same choice in terms of type of contract during the entire sample period. The limit of this sample choice is that our estimate might be less externally valid to the extent that such an inertial behavior is not representative of the Italian retail electricity market. This is a feature that is not uniformly distributed across all the strata of the population.

The switching behavior among domestic households has in fact increased over time, from 13 to 18% at the national level between 2020 and 2023, varying also spatially [1]. Or it may be only partially valid since also the effect of prices on the contract's choice has to be accounted for to say something about the overall effect of prices on the aggregated residential electricity demand.[1] The benefits are a more credible

[1]Notice that it is not straightforward that the overall effect of prices on the aggregated residential electricity demand is smaller, or much smaller, once one has accounted for electricity contract choices. Indeed, one can argue that households might reduce their consumption even if they keep having a fixed-price contract since during periods of high electricity price volatility these have very often a very high fixed price. This was the case in Italy during 2022. Moreover, some utilities chose not to offer fixed-price contracts during the months with the highest volatility.

identification and a more punctual estimate of the price elasticity of electricity consumption, and a higher internal validity.

We find evidence of negative price elasticity to households' electricity consumption at the monthly level. We conducted the analysis both at the monthly and daily level, yielding consistent findings. We find that a response to the price change is not immediate, but spreads out in the months following the change. We report different behaviors of families with variable and fixed-price contracts in response to price changes. Even if within the contract duration, an increase in the PUN leads to a stronger decreased electricity consumption for variable contracts, after the contract drifts, both types of contracts show a significant negative relationship with PUN changes.

This study models residential electricity consumption in a period marked by significant turbulence due to the unprecedented impacts of the COVID-19 pandemic and the energy crisis with escalating electricity prices. Results are particularly important for policymakers and energy providers as they face the complexities of energy supply, demand management, and the transition towards sustainable energy sources amid fluctuating market conditions and societal shifts.

2. Data

For this study we used different sources of administrative information, provided by the utility. First, we use electricity consumption, measured on an hourly basis in kWh. We conduct two sets of analyses, one at a monthly and another at a daily level. In the monthly analyses, we aggregated the observations by summing up the consumption of all the hours of a given month. In the daily analyses, we aggregated the observations at a daily level by taking the sum. For all the contracts in our sample, we know the meter power in kW. [2] We also have information on the geographic location of the household at the city level.

Second, we have a wide range of contractual information that we used to calculate the price each customer faced during the period. First, we use contractual information to distinguish households with variable or fixed-price contracts. In addition, we exploit this contractual data to decompose prices into marginal and fixed com- ponents. [3] In our analyses, we do not consider the fixed components of the actual price faced by the customers and estimate the price elasticity based on exogenous variation of the marginal price. [4]

We combined the administrative data with information on electricity prices in the wholesale markets. Electricity prices are publicly available on the official website of the Italian managing authority of the energetic markets (Gestore dei Mercati Energetici - GME) [2]. We download the monthly and the daily national single price (Prezzo Unico Nazionale - PUN), an index that describes the average price for 1 megawatt/hour

[2]We drop the contracts with a power strictly lower than 3 kilowatts (kW) or strictly higher than 6 kW, as the vast majority of Italian households have a power between 1.5 and 3 kW. The contracts with a very low power might be of houses' belongings (e.g., garage, basement), whereas those with a very high power might be of unusually (and not representative) big houses or small businesses, both outside the scope of this study.

[3]The fixed components are annual, and they can be divided into components predetermined by the national regulatory authority for energy, networks and the environment (ARERA), which are equal for all national customers, and components predetermined by the utility.

[4]Most of the fixed components above will be absorbed by our FE in the empirical specification.

(MWh) of electricity in the Italian wholesale market. The monthly PUN is the index the energy utility uses to calculate the final energy price for its customers when they face a variable price.

We use weather variables from the ERA5-Land [3]. In particular, we consider the following meteorological variables. Heating and cooling degree days (respectively, HDD and CDD); the surface shortwave solar radiation downwards (SSRD), which is a proxy for cloud coverage that directly affects thermal comfort; the relative humidity which affects human comfort. ERA5-Land provides a measure of relative humidity derived from the 2m dew point temperature and the pressure level. For the daily analyses, we also use the average daily temperature and the overall daily average wind speed (along both east-west and north- south directions) aggregated into the Beaufort scale. To match the weather with the contracts' location, we consider the ERA5-Land grid nearest to the town's centroid of the contract. The coordinates of the town's centroids are taken from the Italian National Institute of Statistics (ISTAT).

Given that the analysis spans over the COVID-19 pandemic, we employ measures of mobility restrictions. We included a set of measures that capture the strictness of the restrictions to mobility that the Italian government put in place between 2020 and 2022 in the whole or parts of the national territory. The dataset contains a continuous index that captures the lockdown severity varying at the town-day level. Moreover, it has some more aggregated measures of the territories with similar restrictions in a certain period that span days or months (the so-called white area, yellow area, orange area, and red area).

This combined dataset is a valuable source of information that allow us to capture geographical and time variations in demand-side shifts that are due to COVID-related policies and might confound supply- side shifts.

3. Empirical Strategy and Identification

To study the impact of electricity pricing on household residential consumption, we focused on a balanced panel of 20,422 contracts between January 2020 and March 2023. Covering such a long time horizon helps us accurately account for a wide range of households' structural and behavioral differences that interact with seasonal determinants of electricity consumption and might confound our elasticity estimate. However, many available customers were excluded if information on their electricity consumption was not available during the whole study period. This cut was made to secure a balanced panel of households. We argue that the benefits of a balanced panel data set in this context outweigh its costs. Despite the sample selection, our cluster size is still unusually big if compared with that of other similar studies. Moreover, our specification includes a wide range of fixed effects (FE), accounting for time trends, heterogeneity, and individual-specific seasonality.

Our identification of the electricity price elasticity is based on shocks in the supply side at the national and international levels that affect the price of electricity in the retail markets at the subnational level. This implies that the exposure to the latter price depends on the customer's contract, which is a choice that likely depends also on the retail price itself. In other words, the exogenous shifters of the supply side likely affect our demand composition, making our estimate of the price elasticity less reliable. For example, if an electricity price shock affects the likelihood of activating a fixed-price contract, selection into and out of the sample might make our overall demand less responsive to future shocks. This shock may change the composition of the sample, increasing the proportion of fixed-price contracts. For this reason, we decided to

focus on those contracts that remained active throughout the period despite any events in the international or retail electricity markets.

To estimate the short-run direct response to price fluctuations of the residential electricity demand in Italy, one can employ a log-linear regression of the electricity marginal price faced by each household on their electricity consumption and interpret the coefficient as the price elasticity of the domestic electricity demand. However, this regression may fail to correctly identify the elasticity for at least three reasons: simultaneous bias, endogenous price components, and indirect effects. We are going to discuss each of them.

First, a price change may be due to a shift in either the demand, the supply, or both. When a demand shift induces a price change or is simultaneous to it, the elasticity is not well identified through a simple log- linear regression of consumption on prices. This is the traditional reason why price elasticities are estimated using instrumental variable (IV) strategies. For example, if the observed price increase has been due to a demand increase, the log-linear elasticity estimate would be biased downward, i.e., we would estimate a more inelastic demand. The severity of the bias will depend on the relative shift of the demand with respect to the supply curve and the supply elasticity.

Among all price components, we focus here on the PUN, i.e., the average electricity price in the Ital- ian wholesale electricity market, whereas we will deal with the potential endogeneity of the other price components in the next point.

It may be reasonable to consider the wholesale electricity supply to be highly elastic for the residential electricity demand. However, there might be confounding factors that are driving or are correlated with both the PUN and the domestic electricity demand, even when we aggregate them at the monthly level and try to explain their seasonal variability. In normal times, it is argued that the seasonal variability in the wholesale electricity price is mainly due to supply-side events, e.g., related to the costs of gas, or the marginal technology. Still, a lower but significant variability might be in principle explained by seasonal demand variations. Therefore, we want to tackle this issue directly by appropriately modifying the baseline log-linear specification.

To do so, we control for seasonality in the residential electricity demand at the individual level by in- cluding household-specific month-of-the-year (moy) FE. The household-moy FE accounts for household' patterns of electricity consumption within the year, i.e., seasonal variations in the electricity demand that are specific to each household. Moreover, we control for city-specific weather conditions that affect domes- tic electricity consumption. The full set of weather controls is discussed in the Data section. Both weather and seasonality are known to be the fundamental demand-side factors that might influence the monthly differences in the PUN.

Still, one crucial demand shifter is still missing: the COVID-19 pandemic and the related policy mea- sures. The COVID-19 pandemic burst in Italy in late February 2020 [4]. The Italian government responded to the sharp increase in infection rates, hospitalizations, and deaths with a series of targeted mobility re- strictions. As the pandemic evolved, these mobility restrictions became stricter and stricter, until the whole Italian territory was put under a lockdown measure on the 9th March 2020. The following months were a succession of targeted or full restrictions associated with the spread of the pandemic. The Italian territory was officially divided into three colored zones (that later became four), depending on the strictness of the lockdown measure: white, yellow, orange, and red. Economic sectors, employees, and citizens in general

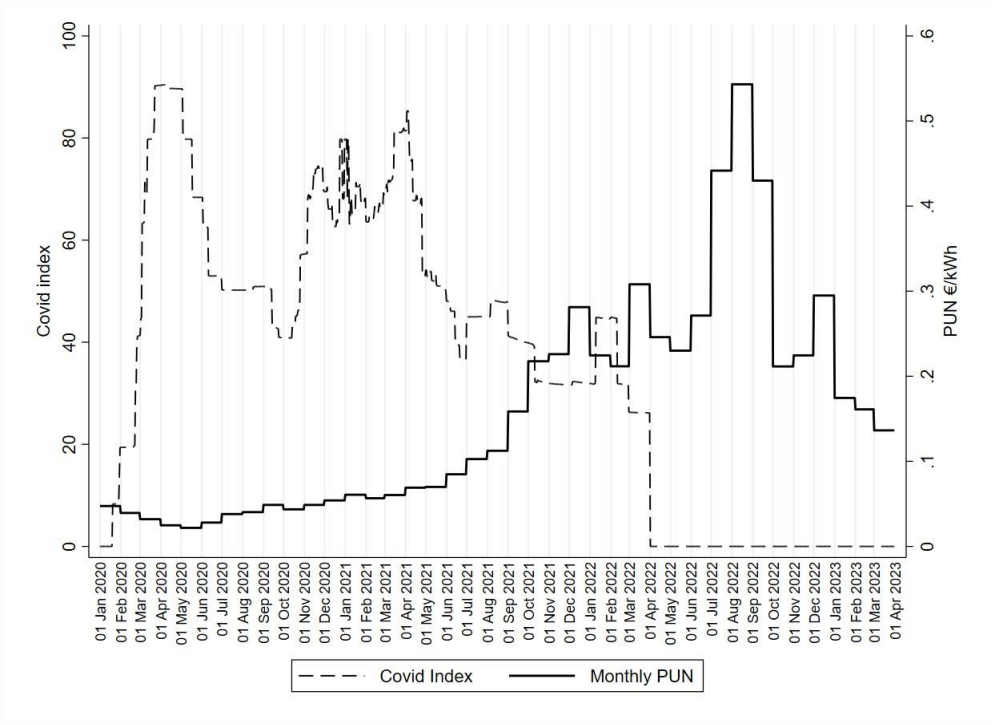

Figure 1: Sample average of the COVID index and monthly PUN parameter (2020-2023).

were heterogeneously affected by these measures. All these restrictions aimed at forcing people to stay at home may have increased the residential electricity demand differently from city to city. If we fail to control for them, we might overestimate the price elasticity, both during and after the so-called lockdown period.

Indeed, during the lockdown period, most of the Italian economy was forced to shut down. As a re- sult, the aggregate electricity demand dropped, and the PUN might have decreased. However, while the electricity demand from the productive sectors considerably diminished, the residential electricity demand may have increased because of the increased time people were forced to spend at home. If so, our elastic- ity estimate would include this spurious negative correlation between the PUN and the domestic demand. Moreover, when the mobility restrictions were lightened, the aggregate electricity demand started to in- crease again, and so did the PUN, while the residential electricity demand may have decreased due to the rediscovered freedom of movement. Again, our elasticity estimate would include a bias in the same direction as before.

In this study, we can observe the strictness of the mobility restrictions at the city level and on a monthly (and even daily) basis thanks to the data set created by two researchers of the Bank of Italy and described in the Data section. Figure 1 shows the time series of the COVID restrictions index sample average along with the monthly PUN. The first wave of restrictions of Spring 2020 is simultaneous to a downward curvature of the monthly PUN. On the other hand, while the mobility measures become harsher in the first half of 2021, the monthly PUN is, if anything, increasing. The positive slope of the PUN is larger in the second half of 2021 and at the beginning of 2022, while the restrictions were gradually softened in the same period. After April 2022, the COVID measures were dismissed, and the PUN exploded. Though the correlation between

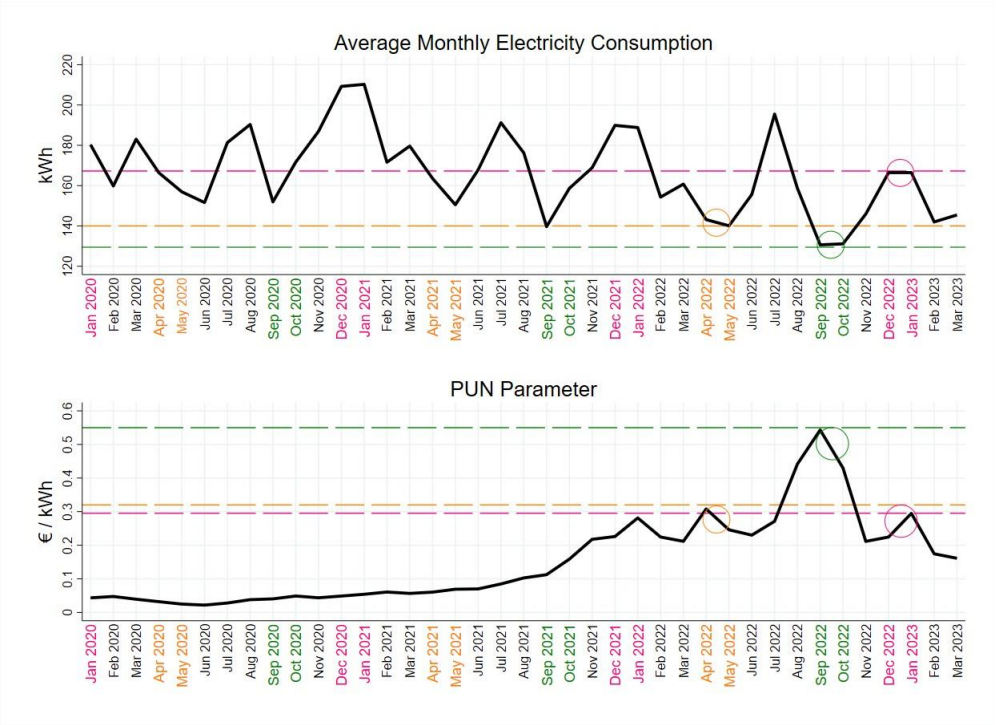

Figure 2: Sample average monthly electricity consumption and PUN parameter (2020-2023).

the two-time series is not heavily marked, a visual inspection also suggests that controlling for the pandemic restrictions is appropriate.

After conditioning on weather, seasonality, and COVID-related mobility restrictions, we argue that the PUN and the residential electricity demand are independent of each other. The average residential electricity demand follows a clear seasonal pattern, as shown in Figure 2. Every year, its peaks are in Winter and Summer, which are the heating and air conditioning periods, while its minima are in Autumn and Spring. On the other hand, the PUN has been relatively stable throughout 2020, with a slight downward curvature in Spring 2020. It started to slightly increase in 2021, especially in the last months, and exploded in 2022, with unprecedented peaks and variations. Therefore, the conditional independence assumption of the PUN, given weather, seasonality, and mobility restrictions, appears to be reasonable. If anything, the average electricity consumption is downward trending, reaching its seasonal minima when the PUN reaches its seasonal maxima. But, at the same time, the simultaneous abnormal variations of the PUN in the second half of the study period are driven by other supply-side factors, a point that we discuss below.

Figure 3 shows a decomposition of the time series of the PUN between January 2020 and March 2023. The black line is the natural logarithmic transformation of the PUN, and the straight line is the reference point of the PUN value in January 2020. The two dotted lines in the lower part of the figure are, respectively, the cumulative increase and decrease in log PUN. The faster the divergence of the two cumulative changes, the higher the variability of the PUN. Moreover, the difference between the two cumulative curves measures how far the PUN is from its reference value, towards higher or lower values.

Despite an already cited decrease followed by an increase in the first semester of 2020, the two cumula-

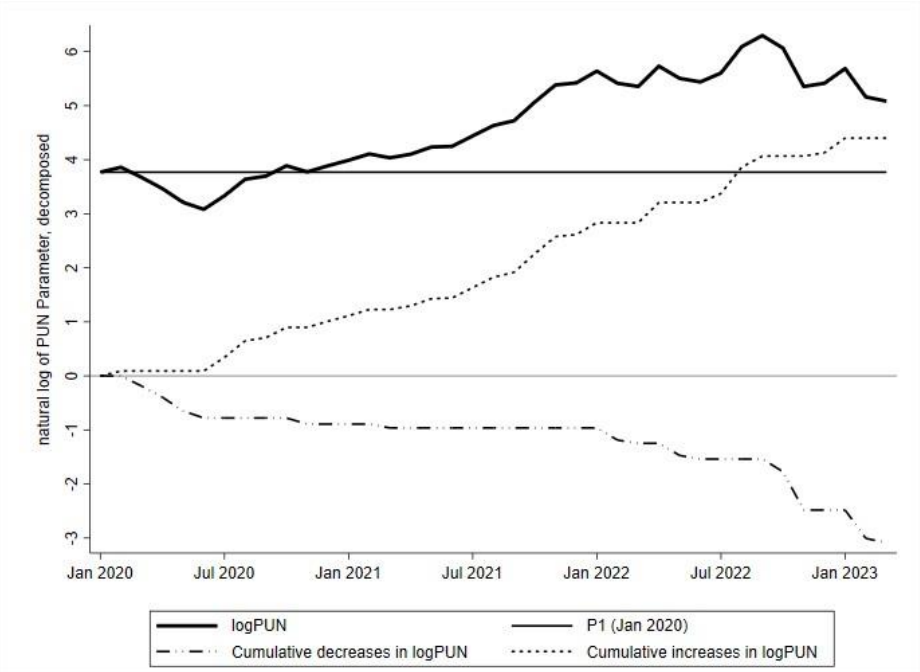

Figure 3: Decomposition of the PUN parameter (January 2020-March 2023).

tive curves are relatively stable during the second semester of 2020 and the first semester of 2021. Thereafter, the cumulative increase starts to diverge until January 2022, after which both curves are increasingly divergent. Overall, the difference between the two curves in both 2021 and 2022 is positive, with an increasing trend. The visual pattern is clear, and it suggests that the time series of the logarithmic wholesale electricity prices suddenly changed its mean and variance in late 2021.

A clue of what might be the key driver of this change can be grasped from Figure 4. The figure shows the times series of the PUN along with the two main indexes of gas prices in the Italian wholesale gas markets. Both series are in EUR/kWh. The changes are almost parallel in their direction during the whole study period. This is not surprising because gas is the marginal technology of electricity in Italy, i.e., the technology that clears the wholesale electricity market in every period, and therefore, it is the main driver of electricity prices. The visual correlation between the indexes is straightforward and present in the first half of 2020. The reason why the wholesale gas prices went insane starting in late 2021, can be attributed to the geopolitical tensions between Russia and Ukraine, which led to an open armed conflict in February 2022 [5].

Given its dependence on the gas market and the exceptional nature of the period under study for the price consequences of geopolitical tensions, the conditional independence of the PUN appears to be nat- ural, as a measure of supply shifts that are not confounded with simultaneous demand shifts after all the appropriate controls discussed above are conditioned for. Therefore, the PUN is a good candidate to be the exogenous instrument in our log-linear regression augmented with household-specific FE, city-specific weather, and COVID-related measures.

Endogenous price components represent the second threat to identifying the price elasticity of electric-

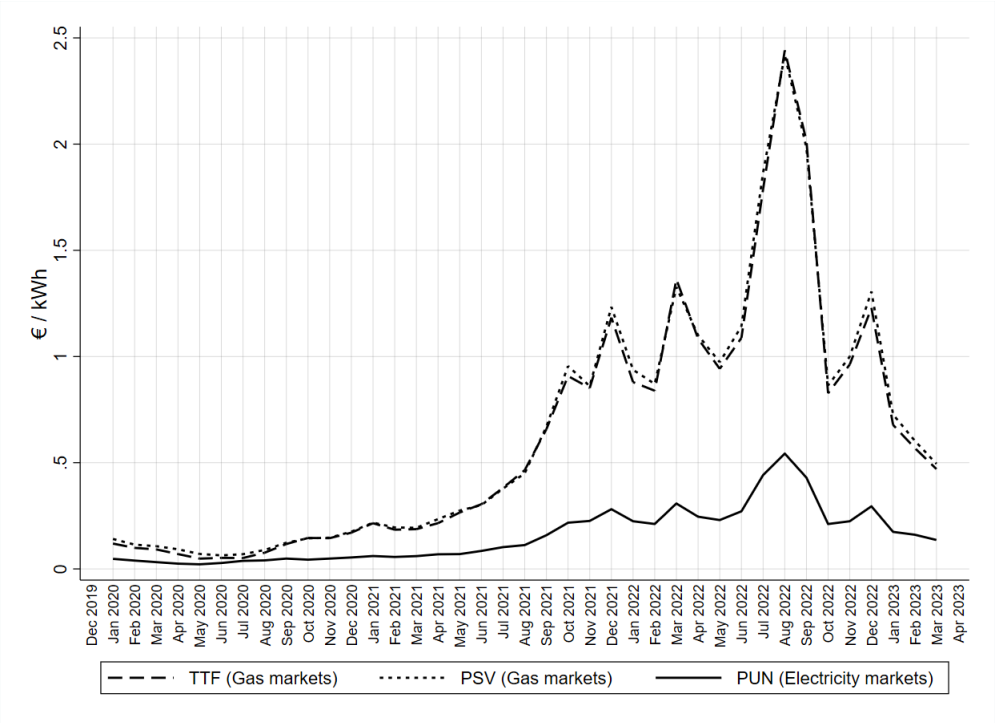

Figure 4: PUN parameter and gas prices in the Italian wholesale gas markets.

ity consumption. Each household in our sample self-selected into a contract with certain characteristics and into the retail market in a certain period. Above, we have described all the possible components of the gross electricity price for the contracts in our sample. Here, it is sufficient to recall that a main difference is between variable and fixed-price contracts, the former with the electricity price indexed to the current (or previous) monthly PUN, while the latter having a fixed sharp electricity price for a predetermined number of months, after which they are also indexed to the PUN. The self-selection of households into one contract type or the other can bias our estimate if, for example, households who are less responsive to price changes self-selected into a variable contract. We tackle this issue by including household FE in our augmented specification. Such FE accounts for unobserved and time-invariant household differences concerning con- sumption habits and preferences. Notice that the above-mentioned household-by-moy FE also helps us in disentangling systematic differences between households in terms of consumption predictable routines.

We present all our estimates with both ordinary least squares (OLS) and two-stage least squares (2SLS), where the instrument is the monthly PUN. The instrumented regression cleans up for any remaining endo- geneity in the marginal price faced by each household.

The third threat to our identification strategy concerns the indirect effects of wholesale electricity prices on household electricity consumption. Theoretically, prices affect consumption through a substitution and an income effect. Households substitute the relatively more expensive electricity good for other goods. When electricity is more costly, families may decide to cut electricity consumption, and keep the savings for something else. At the same time, their real income decreases as electricity prices increase, and it is unclear what the resulting response is in terms of electricity consumption. On the one side, a family that

considers electricity to be a normal good has a positive income effect. As its income increases, its electricity consumption decreases (since the family is poorer or less rich than before, it demands less electricity). On the other side, for some households electricity could represent an inferior good; or for the same household once a certain income level is surpassed. For example, when the family income decreases, the household can decide to spend more time at home, increasing electricity consumption. In our context, we cannot identify either substitution or income effects alone, but at most their cumulative effect, or not even it.[5]

In fact, the effect of the wholesale electricity prices went far beyond the only response of residential consumption. Electricity is a key input for most (or all) productive processes, and a permanent rise in its price likely translates into a general rise in the prices of many goods and services. Indeed, the unprecedented increases in the PUN were followed by an increase in inflation in Italy and Europe [6], with little to no precedents in recent history. The increases were not homogeneous, with goods and services produced with energy-intensive processes being the most affected in a very short period. As a result, it is unreasonable to claim that the effect of the PUN on electricity consumption goes only through the marginal prices faced by households. Technically, the exclusion restriction of our instrument is likely violated. Indeed, all the prices of goods that have been affected by the PUN increases and that are in the consumption bundles of in-sample households have other income and substitution effects on their electricity consumption. It is hard to identify the precise effect of the marginal price of electricity without making restrictive and perhaps unreasonable assumptions.

We deal with this issue in two ways. First, we provide the estimates for the main models with a specification that includes time FE (month, month-by-city, or day/day-by-city). The time FE captures all the economy-wide (or city-wide) shocks that are common to all households. In our case, above all are the indirect effects. If one is willing to assume that all the indirect effects are common to all households and captured at the monthly (or daily) level, our estimate of interest identifies the direct effect of electricity prices. This assumption is perhaps more reasonable when the time FE are city-specific, allowing for differ- ences in the economic structures between cities, and when the time FE are at the daily level as in our daily analyses. However, this strategy has a major drawback, which comes from the fact that our instrument, the PUN, varies at a monthly level, and therefore the variation it induces is partly absorbed by the time FE. The residual variation after conditioning on the time FE is given both by fixed contracts that are not drifted (see the Data section) and by contracts indexed to the PUN of the previous month.

Nonetheless, the absorption might be substantial, and we might pay this price for a benefit, the exact identification, that relies on an assumption that the reader is perhaps not willing to take. Therefore, we present all estimates of our augmented specification with and without time FE. The caveat to keep in mind is that they identify different estimands. For the augmented specification without time FE in particular, the estimate of interest identifies a total effect of the PUN on the household's electricity consumption in our sample.

To sum up, our main specification is the following:

[5]Starting from Fall 2021, the Italian government put in place a policy of targeted subsidies to compensate low-income households for the electricity price increases. In principle, one might exploit the compensations to try to disentangle the substitution from the income effect. Unfortunately, we do not observe whether a household in our sample was subsidized or not, nor the subsidy level.

$$lnE_{ict} = \alpha^1_{ict} FE_{ict} + \alpha^2_{ct} W_{ct} + \alpha^3_{ct} R_{ct} + \beta lnP_{it} + \epsilon_{ict}$$

where E_{ict} is the total electricity consumption in kWh of contract i associated with a house located in city c in period t, FE_{ict} is a vector of FE, W_{ct} is a vector of weather controls in city c and period t, R_{ct} is a vector of COVID-related restrictions in city c and period t, P_{it} is the total marginal price of contract i in period t and ϵ_{it} is an error term clustered at the city-time level (two-way clustering). Our estimate of interest is β. The vector FE_{ict} used is made explicit in each table of results. The regressions are estimated by OLS, after absorbing some computationally-demanding FE.

We provide the results of the analyses both at the monthly and the daily level. At the monthly level, we include three sets of FE: 1) contract and contract-by-moy (month of the year); 2) contract, contract-by-moy and month; 3) contract, contract-by-month, and month-by-city.

When the month FE are specified, we remove the monthly level control for COVID-related restrictions due to collinearity. Similarly, in the specification with the month-by-city FE, we drop the COVID-19 restrictions and the city meteorology.

At the daily level, we provide the results for six different specifications, that mainly vary for the set of FE included, and the collinear controls excluded: 1) contract, contract-by-moy, contract-by-dow (day of the week), dow-by-moy, monthly-level COVID-related control; 2) contract, contract-by-moy, contract-by-dow, dow-by-moy, daily-level COVID-related control; 3) contract, contract-by-moy, contract-by-dow, dow-by-moy, daily-level COVID-related control, month; 4) contract, contract-by-moy, contract-by-dow, dow-by-moy, month-by-city; 5) contract, contract-by-moy, contract-by-dow, dow-by-moy, day; 6) contract, contract-by-moy, contract-by-dow, dow-by-moy, day-by-city.

Again, for collinearity, we appropriately remove city weather and COVID-related controls. Finally, the daily specifications also contain a vector of national holiday indicators.

As discussed above, we present the OLS and the 2SLS results. We also present the estimates from a variety of heterogeneous analyses.

At the monthly level, we study the heterogeneous price response for the contract's power in kW, the recent price trend, and the recent price level. Furthermore, we explore the medium-term price response by allowing a permanent price change to have a lagged effect on consumption from three to six months. In addition, we investigate the differential response to the PUN parameter of fixed versus variable contracts and for fixed contracts, from not-yet drifted to drifted periods. The latter exercise might be seen as a step towards disentangling the direct and indirect effects of the PUN.

At the daily level, we study whether the response differs on weekdays as opposed to weekends. Finally, we examine whether households subject to the PUN of the previous month respond to the daily PUN and its lags after controlling for the daily marginal price. The last set of estimates is a preliminary test for a behavioral response to the salience of electricity price hikes.

Table 1: Main result - OLS

OLS	$ln(y_{it})$		
	(1)	(2)	(3)
$ln(p_{it})$	-0.08692***	-0.02327***	-0.02225***
	(0.0129)	(0.0052)	(0.0053)
Lockdown area: White	0.00718		
	(0.0206)		
Lockdown area: Yellow	0.04785**		
	(0.0190)		
Lockdown area: Red	0.10916***		
	(0.0168)		
Observations	796,458	796,458	789,555
Adj. R2	0.67605	0.68157	0.68231
Fixed effects:			
Contract	x	x	x
Contract by month of year	x	x	x
Month		x	
Month by city			x
City weather	x	x	

Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Notes: Log-log OLS regressions, robust standard errors in parentheses. The dependent variable is the total electricity consumption in kWh of contract i in period t. p_{it} is the total marginal price of contract i in period t. $Lockdown\ Area$ is a factorial of COVID-related restrictions. All regressions control for contract and contract-by-moy FE. In addition, the regression under column (1) controls for city weather, the one under column (2) controls for month FE and city weather, and the one under column (3) for month-by-city FE. $City\ weather$ is a vector of weather controls.

4. Results

In this section, we provide selected coefficients of linear regressions for the price elasticity of household electricity consumption in the Italian retail market in a time characterized by multiple external shocks, namely the COVID-19 pandemic, the energy crisis, and the Ukraine war.

Tables 1 and 2 show results for the OLS and 2SLS models, respectively. Standard errors are robust and clustered at the city-time level. The dependent variable is the total electricity consumption in kWh of contract i associated with a house located in the city c in period t. Our coefficient of interest is the one of the marginal electricity price, p_{it}. Moreover, all regressions control for contract and contract-by-moy FE. $City\ weather$ is a vector of weather controls. $Lockdown\ area$ is a factorial of COVID-related restrictions. The specification in column (1) includes the marginal price, lockdown patterns, city meteorology, and contract and contract-by-moy FE as independent variables. The one under column (2) includes city weather and month FE. Finally, the one under column (3) includes month by city FE.

Table 2: Main result - 2SLS

2SLS	$ln(y_{it})$		
	(1)	(2)	(3)
$ln(p_{it})$	-0.11551***	-0.04780**	-0.04948**
	(0.01432)	(0.01878)	(0.02021)
Lockdown area: White	-0.00105		
	(0.01980)		
Lockdown area: Yellow	0.04768**		
	(0.01791)		
Lockdown area: Red	0.09451***		
	(0.01665)		
Observations	796,458	796,458	789,555
Fixed effects:			
Contract	x	x	x
Contract by month of year	x	x	x
Month		x	
Month by city			x
City weather	x	x	

Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Notes: Log-log 2SLS regressions, robust standard errors in parentheses. The dependent variable is the total electricity consumption in kWh of contract i in period t. p_{it} is the total marginal price of contract i in period t. Lockdown area is a factorial of COVID-related restrictions. All regressions control for contract and contract-by-moy FE. In addition, the regression under column (1) controls for city weather, the one under column (2) controls for month FE and city weather, and the one under column (3) for month-by-city FE. City weather is a vector of weather controls.

The month of sample FE consider common shocks to the electricity demand that might confound supply-side shocks, such as inflation, COVID-related national policies, or global trends. They are rather restrictive and highly correlated with our key explanatory variable. However, they are arguably important to con- sider in turbulent times (COVID recession, post-COVID recovery, inflation, and war-related crises). So, we present all the different specifications.

We find evidence of negative price elasticity to households' electricity consumption at the monthly level, controlling for COVID-19 lockdown restrictions, contract and time specificities, and meteorology. As expected, the stricter the lockdown restrictions, the higher the consumption. Notice, though, that such specification might be subject to endogeneity. For instance, cities, where households spend less time at home and have lower electricity consumption, could be the same areas where the COVID-19 virus has spread the most and where restrictive measures may have become stricter with time due to more infections. This may induce a downward bias.

In Tables 3 and 4, we study the monthly heterogeneous price response with respect to the contract's meter power in kW (Panel A), the recent price trend, whether increasing or decreasing (Panel B); and the recent price level (Panel C). All regressions control for contract and contract-by-moy FE. In addition, re- gressions under column (1) control for city weather and lockdown areas, those under column (2) control for month FE and city weather, and those under column (3) for month-by-city FE. In Panels A and B, errors are clustered at the city-month level, while in Panel C, only at the city level. Results are consistent with previous models. For instance, row 1 shows the price elasticity on consumption given a meter's power of 3 kW.

In Tables 5 we show the behavioral response to the monthly price changes. To explore the medium-term price response we allow a permanent price change to have a lagged effect on consumption from three to six months. Regression under column (1) includes the marginal price plus its lags from t_{-1} to t_{-3}, the one under column (2) from t_{-1} to t_{-4}, the one under column (3) from t_{-1} to t_{-5}, and the one under column (4) from t_{-1} to t_{-6}. The total elasticity j months after a permanent price change corresponds to the sum of all price coefficients with and without lag, where j is the total number of months to time t. For each parameter, both the OLS and 2SLS versions are displayed. All specifications point towards a non-significant response to price in the current and following month after the change. The effect is negative and significant starting from the second month. In the OLS specifications, they all imply a total elasticity of about -10% in 3 to 6 months. In the 2SLS models, the total effect is larger, up to -17%. This suggests that the response to the permanent price change is not immediate, but spreads out in the months following the change. Such closer inspection seems to imply that the response of the residential electricity consumption to a price change in the medium run might depend on the permanence of the change. In Figure A.2, we show the total cumulative elasticity month by month of the 6-month specification.

We also investigate the differential response of fixed versus variable contracts to the PUN parameter, and for fixed contracts from not-yet drifted to drifted periods. Such exercise might be a way to disentangle the direct and indirect effects of the PUN.

The analysis in Table 6 underscores different behaviors between variable and fixed contracts in response to the PUN. $1(t - t_{i1} > dur_i)$ indicates the effect when the contract has drifted from a fixed to a variable price. $ln(parPUN_t)$ x $1(t - t_{i1} \leq dur_i)$ indicates the PUN of the previous month when the contract has not expired yet. Complementarily, $ln(parPUN_t)$ x $1(t - t_{i1} \leq dur_i)$ is the PUN parameter after the drift.

Table 3: Heterogeneity by meter's power (Panel A), price trend in the last 3 months (Panel B), and current price level (Panel C) - OLS

OLS	$ln(y_{it})$		
	(1)	(2)	(3)
Panel A: Meter's power			
$ln(p_{it})$ x			
$\mathbb{1}(power = 3\ kW)$	-0.08714***	-0.02341***	-0.02243***
	(0.0128)	(0.0051)	(0.0052)
$\mathbb{1}(power = 4.5\ kW)$	-0.07662***	-0.01385	-0.01214
	(0.0150)	(0.0095)	(0.0096)
$\mathbb{1}(power = 6\ kW)$	-0.10381***	-0.04115**	-0.04078**
	(0.0232)	(0.0187)	(0.0191)
Adj. R2	0.67607	0.68158	0.68233
Panel B: Price trend			
$ln(p_{it})$ x			
$\mathbb{1}(p_{it} > p_{it_{-1}} > p_{it_{-2}})$	-0.10269***	-0.02993***	-0.02819***
	(0.0146)	(0.0052)	(0.0051)
$\mathbb{1}(p_{it} < p_{it_{-1}} < p_{it_{-2}})$	-0.06305***	-0.02354***	-0.02146***
	(0.0139)	(0.0048)	(0.0047)
$\mathbb{1}(else)$	-0.08771***	-0.02572***	-0.02453***
	(0.0119)	(0.0050)	(0.0051)
Adj. R2	0.67672	0.68158	0.68232
Panel C: Price level			
$ln(p_{it})$ x			
$\mathbb{1}(p_{it} < 0.20)$	-0.09495***	-0.02266***	-0.01775**
	(0.0157)	(0.0081)	(0.0075)
$\mathbb{1}(0.20 \leq p_{it} < 0.30)$	-0.10122***	-0.02187***	-0.02168***
	(0.0242)	(0.0064)	(0.0069)
$\mathbb{1}(p_{it} \geq 0.30)$	-0.11601***	-0.03310***	-0.03492***
	(0.0293)	(0.0099)	(0.0115)
Adj. R2	0.67612	0.68157	0.68231
Observations	796,458	796,458	789,555
Fixed effects:			
Contract	x	x	x
Contract by month of year	x	x	x
Month		x	
Month by city			x
City weather	x	x	
Lockdown area	x		

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Notes: Log-log OLS regressions, robust standard errors clustered at the city-time level in parentheses. The dependent variable is the monthly total electricity consumption in kWh of contract i in period t. p_{it} is the monthly total marginal price of contract i in period t. In Panel A, it interacts with the meter's power levels; in Panel B, it interacts with price trend levels; in Panel C, it interacts with price levels. All regressions control for contract and contract-by-moy FE. In addition, the regression under column (1) controls for city weather and lockdown areas, the one under column (2) controls for month FE and city weather, and the one under column (3) for month-by-city FE. City weather is a vector of weather contr$_{10}$$_{5}$ls. Lockdown area is a factorial of COVID-related restrictions.

Table 4: Heterogeneity by meter's power (Panel A), price trend in the last 3 months (Panel B), and current price level (Panel C) - 2SLS

2SLS	$ln(y_{it})$		
	(1)	(2)	(3)
Panel A: Meter's power			
$ln(p_{it})$ x 1(power = 3 kW)	-0.11623***	-0.04877**	-0.05041**
	(0.0143)	(0.0200)	(0.0214)
$ln(p_{it})$ x 1(power = 4.5 kW)	-0.10348***	-0.03729**	-0.03927**
	(0.0168)	(0.0151)	(0.0171)
$ln(p_{it})$ x 1(power = 6 kW)	-0.12204***	-0.05601**	-0.05728**
	(0.0269)	(0.0227)	(0.0246)
Panel B: Price trend			
$ln(p_{it})$ x 1($p_{it} > p_{it-1} > p_{it-2}$)	-0.12371***	-0.06961**	-0.07219**
	(0.0150)	(0.0261)	(0.0279)
$ln(p_{it})$ x 1($p_{it} < p_{it-1} < p_{it-2}$)	-0.08962***	-0.05953**	-0.06138**
	(0.0143)	(0.0234)	(0.0250)
$ln(p_{it})$ x 1(*else*)	-0.11330***	-0.06376**	-0.06663**
	(0.0133)	(0.0243)	(0.0259)
Panel C: Price level			
$ln(p_{it})$ x 1(p < 0.20)	-0.21895***	-0.01723	-0.01774
	(0.0284)	(0.0266)	(0.0282)
$ln(p_{it})$ x 1(0.20 ≤ p < 0.30)	-0.28217***	0.03443	0.03600
	(0.0391)	(0.0342)	(0.0364)
$ln(p_{it})$ x 1(p ≥ 0.30)	-0.38774***	0.05258	0.05494
	(0.0581)	(0.0539)	(0.0559)
Observations	796,458	796,458	796,555
Fixed effects:			
Contract	x	x	x
Contract by month of year	x	x	x
Month		x	
Month by city			x
City weather	x	x	
Lockdown area	x		

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Notes: Log-log 2SLS regressions, robust standard errors in parentheses. In Panel A, errors are clustered at the city and month level, while in Panel C, only at the city level. The dependent variable is the monthly total electricity consumption in kWh of contract i associated with a house located in the city c in period t. p_{it} is the monthly total marginal electricity price of contract i in period t. In Panel A, it interacts with the meter's power levels; in Panel B, it interacts with price trend levels; in Panel C, it interacts with price levels. All regressions control for contract and contract-by-moy FE. In addition, regressions under column (1) control for city weather and lockdown areas, those under column (2) control for month FE and city weather, and those under column (3) for month-by-city FE. City weather is a vector of weather controls. Lockdown area is a factorial of COVID-related restrictions.

Table 5: Dynamics - OLS and 2SLS

		(1)	(2)	(3)	(4)
$ln(p_{it})$					
	OLS	-0.00279	-0.00004	-0.00444	-0.01286
		(0.01938)	(0.01317)	(0.01324)	(0.01162)
	2SLS	-0.00827	-0.00068	0.00150	-0.00757
$ln(p_{it-1})$		(0.02758)	(0.01216)	(0.00859)	(0.00705)
	OLS	-0.02788	-0.01824	-0.00556	0.00453
		(0.02587)	(0.01468)	(0.01512)	(0.01495)
	2SLS	-0.03144	-0.00129	0.02174*	0.03070***
$ln(p_{it-2})$		(0.04322)	(0.01822)	(0.01236)	(0.01089)
	OLS	-0.04007**	-0.06782***	-0.06460***	-0.05769***
		(0.01904)	(0.01372)	(0.01274)	(0.01256)
	2SLS	-0.07303**	-0.12759***	-0.12073***	-0.11608***
$ln(p_{it-3})$		(0.03367)	(0.01912)	(0.01612)	(0.01024)
	OLS	-0.03327**	0.07546***	0.05962***	0.04666***
		(0.01301)	(0.01713)	(0.01502)	(0.01497)
	2SLS	-0.03550	0.10196***	0.06666***	0.06758***
$ln(p_{it-4})$		(0.02289)	(0.02025)	(0.02301)	(0.01867)
	OLS		-0.09743***	-0.05857***	-0.05814***
			(0.01324)	(0.01416)	(0.01311)
	2SLS		-0.12438***	-0.07567***	-0.08278***
$ln(p_{it-5})$			(0.01224)	(0.02084)	(0.01553)
	OLS			-0.03950***	0.00281
				(0.00983)	(0.01342)
	2SLS			-0.05704***	-0.02520*
$ln(p_{it-6})$				(0.01387)	(0.01316)
	OLS				-0.04203***
					(0.00971)
	2SLS				-0.03732***
					(0.00840)
Total elasticity j months after a permanent price change					
	OLS	-0.10401	-0.10806	-0.11305	-0.11671
		(0.01201)	(0.00947)	(0.00947)	(0.00934)
	2SLS	-0.14823	-0.15199	-0.16353	-0.17067
		(0.01252)	(0.00699)	(0.00794)	(0.00800)
Observations		735,192	714,770	694,348	673,926
Nr. periods		36	35	34	33

Notes: Log-log OLS and 2SLS regressions, robust standard errors clustered at the city and month level in parentheses. The dependent variable is the monthly total electricity consumption in kWh of contract i associated with a house located in the city c in period t. p_{it} is the monthly total marginal price of contract i in period t. Regression under column (1) includes its lags from $t-1$ to $t-3$, the one under column (2) from $t-1$ to $t-4$, the one under column (3) from $t-1$ to $t-5$, and the one under column (4) from $t-1$ to $t-6$. The total elasticity j months after a permanent price change is the sum of all price coefficients with and without lag, where j is the total number of months to time t. All regressions control for contract and contract by month of the year FE, plus city weather.

Table 6: Direct and indirect effect of the PUN parameter

OLS	$ln(y_{it})$	
	(1)	(2)
$1(t - t_{i1} > dur_i)$	0.05014	-0.03828*
	(0.03848)	(0.02030)
$ln(parPUN_t)$ x $1(t - t_{i1} \leq dur_i)$	-0.07280***	-0.03851***
	(0.01162)	(0.00599)
$ln(parPUN_t)$ x $1(t - t_{i1} > dur_i)$	-0.04338***	-0.04287***
	(0.00892)	(0.00599)
Price type at t_{i1}	*Variable*	*Fixed*
Observations	56,628	738,933
Adj. R^2	0.72212	0.67184
Fixed effects:		
Contract	x	x
Contract by month of year	x	x
City weather	x	x
Lockdown area	x	x

Two-way clustering: city level and month of sample level.

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Notes: Log-log OLS regressions, robust standard errors clustered at the city and month level in parentheses. The dependent variable is the monthly total electricity consumption in kWh of contract i associated with a house located in the city c in period t. dur_i is the contract's duration from the activation date up to its expiration, i.e., when the contract drifts from a fixed to a variable price. $parPUN_t$ is the average monthly PUN at t_{-1}. $ln(parPUN_t)$ x $1(t - t_{i1} \leq dur_i)$ indicates the PUN of the previous month when the contract has not expired yet. $ln(parPUN_t)$ x $1(t - t_{i1} \leq dur_i)$ is the PUN parameter after the drift. The regression under column (1) refers to a variable price type at t_{i1}, while the one under column (2) refers to a fixed type. City weather is a vector of weather controls. Lockdown area is a factorial of COVID-related restrictions. All regressions control for contract and contract-by-moy FE, city weather, and lockdown areas.

We find that families with variable-price contracts show a more pronounced decrease in consumption with an increase in electricity price within the contract duration, likely due to the direct impact of price signals on consumer behavior. Interestingly, families with fixed-price contracts before the drift seem to be as well responsive to the PUN parameter. Post-drift, both contract types exhibit a similar decrease in consumption in response to PUN increases, indicating that regardless of the initial contract type, the end of contract duration and subsequent exposure to variable pricing lead to more responsive consumption behavior.

Even if within the contract duration, an increase in the PUN leads to a stronger decreased electricity consumption for variable contracts, after the contract drifts, both types of contracts show a significant negative relationship with PUN changes. However, the sensitivity to the PUN parameter of the variable types is lower after the duration. This might be due to a decreasing sensitivity over time of variable types, or to the fact that the PUN parameter is not the sole component of the marginal price, and the other compo- nents are countercyclical in the last part of the sample (to combat the increases). This way, the systematic measurement error biases the elasticity downwards.

A caveat of this piece of analysis is that the month FE cannot be added because they would absorb the PUN parameter.

Table 7, we look at the very short-term effect on consumption for contracts indexed to the PUN of the previous month ($parPUN$), using the daily total electricity consumption in kWh of contract i in period t as dependent variable. This last set of estimates is considered preliminary tests for a behavioral response to the salience of electricity price hikes. p_{it} is the daily total marginal price of contract i in period t. $Holidays$ is a national holiday indicator. $COV\ IDmeasuresindex$ is a continuous index capturing the lockdown severity varying at the town and daily levels. All regressions include p_{it} and its daily lags from t_{-1} to t_{-4}, and control for contract, contract-by-moy, contract-by-dow, dow-by-moy FE, city weather, and holidays. In addition, the regression under column (1) controls for lockdown areas, the one under column (2) controls for the COVID measures index, and the one under column (3) controls for month-by-city FE. Interestingly, most daily lagged PUN coefficients are not significant as opposed to the daily PUN level, giving a sense of the salience of the peak. Standard errors are robust and clustered at the city and daily levels.

In Tables B.1 and B.2, we show the analysis at the daily level with OLS and 2SLS, respectively. Across all models (1-6), the coefficient of the marginal price is consistently negative and statistically significant. As in the monthly analyses, the coefficients for the yellow and red areas are positive and statistically significant, suggesting higher electricity consumption in regions with more stringent lockdown measures, possibly due to increased home activities during lockdowns. The COVID measures index, a continuous variable capturing the severity of lockdowns, also shows a positive and significant effect on electricity consumption, further supporting the finding that more severe restrictions are associated with increased electricity usage.

In Table B.3, at the daily level, we study whether the response differs on weekdays as opposed to weekends. Across all models, the coefficients are negative and statistically significant, indicating that an increase in the marginal price of electricity leads to a decrease in electricity consumption both on weekdays and weekends. However, the effect on weekends is slightly smaller. The magnitude of the effect decreases slightly across the models, from about -0.06 in model (1) to -0.016 in model (3), suggesting a consistent but varying sensitivity to price changes depending on the specification.

Table 7: Daily PUN among contracts indexed to the PUN of the previous month (*parPUN*) - OLS

OLS	$ln(y_{it})$		
	(1)	(2)	(3)
$ln(p_{it})$	-0.04589***	-0.03823***	-0.02255***
	(0.00497)	(0.00547)	(0.00351)
$ln(daily\ pun_t)$	-0.09203**	-0.07512**	-0.04851
	(0.03700)	(0.03481)	(0.03438)
$ln(daily\ pun_{t-1})$	0.04811	0.05187	0.06181*
	(0.03891)	(0.03888)	(0.03688)
$ln(daily\ pun_{t-2})$	0.01979	0.02492*	0.02836**
	(0.01561)	(0.01482)	(0.01247)
$ln(daily\ pun_{t-3})$	-0.00293	0.00032	0.01330
	(0.01508)	(0.01422)	(0.01180)
$ln(daily\ pun_{t-4})$	-0.00215	0.00840	0.02895**
	(0.01308)	(0.01252)	(0.01146)
Observations	24,193,214	24,193,214	24,193,214
Adj. R^2	0.57938	0.58016	0.58808
City weather	x	x	x
Holidays	x	x	x
Fixed effects:			
Contract	x	x	x
Contract by month of year	x	x	x
Contract by day of week	x	x	x
Day of week by month of year	x	x	x
Month			
Month by city			x
Lockdown area	x		
COVID measures index		x	

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Two-way clustering: city level and day of sample level.

Only contracts indexed to the PUN of the previous month (*parPUN*) are included.

Note: Log-log OLS regressions, robust standard errors clustered at the city and day level in parentheses. The dependent variable is the daily total electricity consumption in kWh of contract i in period t. p_{it} is the daily total marginal price of contract i in period t. Holidays is a national holiday indicator. Lockdown area is a factorial of COVID-related restrictions. COV ID measures index is a continuous index capturing the lockdown severity varying at the town and daily levels. All regressions include p_{it} and its daily lags from t_{-1} to t_{-4}, and control for contract, contract-by-moy, contract-by-dow, dow-by-moy FE, city weather, and holidays. In addition, the regression under column (1) controls for lockdown areas, the one under column (2) controls for the COVID measures index, and the one under column (3) controls for month-by-city FE. Only contracts indexed to the PUN of the previous month (parPUN) are included.

5. Conclusion

In this work, we are interested in isolating the direct short-term effect of prices on electricity consumption using a unique data set of Italian household electricity usage. We leverage variations from the supply side, while keeping our observed demand constant. Specifically, we calculate the price elasticity of demand based on pre-selected, unaltered electricity contracts. Our analysis is conducted both at the monthly and daily level, yielding consistent findings. Our baseline specification takes advantage of various exogenous shocks, namely the marginal electricity price and COVID-related restrictions. We also employ a full set of fixed effects to control for time-invariant differences across households and over time. We find evidence of a negative price elasticity. The monthly price elasticity varies depending on the specification and is higher for the IV approach. The pattern is confirmed at the daily level. We conduct a range of heterogeneity analyses as well. At a monthly level, we study the variability in price responsiveness in relation to the contract's power capacity (measured in kW), recent price trends, and price levels. Additionally, we evaluate the medium-term impact of permanent price changes, examining lagged consumption effects over three to six months. We further explore how consumption responds to the national single price (PUN) based on contract type — fixed versus variable. For fixed contracts, we compare periods before and after price drifts. We find that there is some evidence of short-lived behavioral response to the PUN parameter. This analysis could shed light on the direct versus indirect influences of the PUN on consumption. On a daily basis, we investigate differences in consumption responses between weekdays and weekends. Lastly, we probe how households with a contract indexed to the PUN of the previous month react to daily PUN figures when accounting for their marginal price. These latter findings serve as an initial inquiry into behavioral reactions to the prominence of electricity price increases.

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Appendix

A Figures

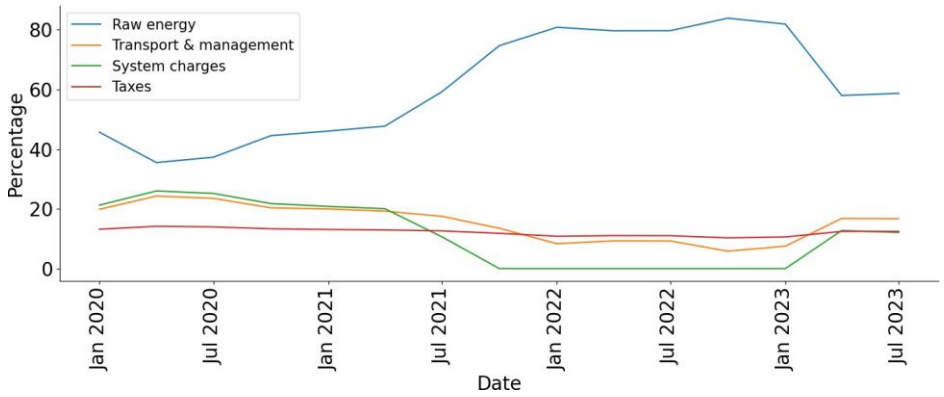

Figure A.1: Percentage weight of electricity costs by category and trimester between 2020 and 2022 for a family with 3 kW of electrical meter power and 2,700 kWh of annual consumption in the protected market.

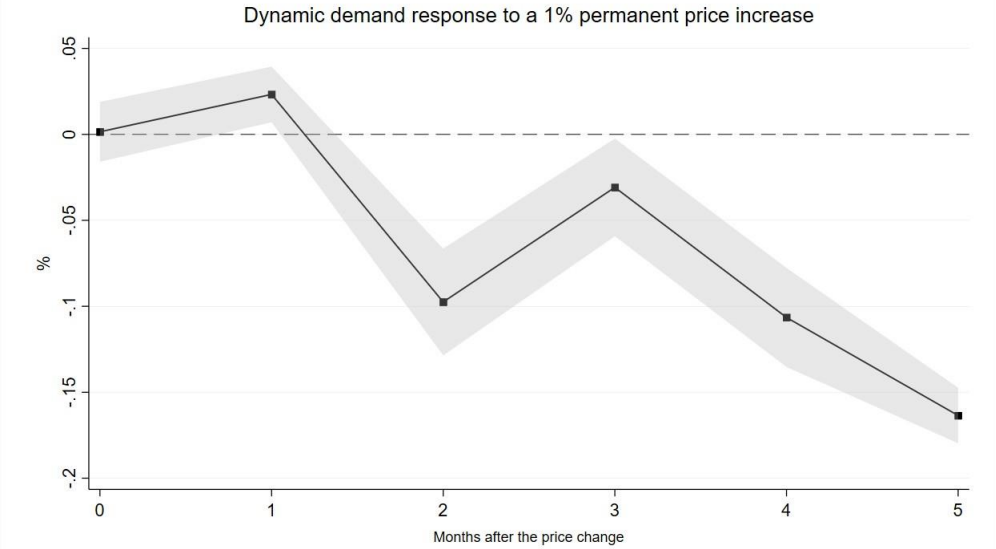

Figure A.2: Dynamic demand response to a 1% permanent price increase.

B Tables

Table B.1: Daily Analysis - OLS

OLS	$ln(y_{it})$					
	(1)	(2)	(3)	(4)	(5)	(6)
$ln(p_{it})$	-0.09315***	-0.02616*	-0.02366***	-0.02257***	-0.02395***	-0.02257***
	(0.0116)	(0.0148)	(0.0056)	(0.0058)	(0.0036)	(0.0034)
Lockdown area: White	0.03042*					
	(0.0159)					
Lockdown area: Yellow	0.08971***					
	(0.0230)					
Lockdown area: Red	0.13253***					
	(0.0171)					
COVID measures index		0.00232***	0.00106***			
		(0.0003)	(0.0004)			
Observations	24,220,492	24,220,492	24,220,492	24,220,492	24,220,492	24,010,570
Adj. R^2	0.57902	0.58014	0.58321	0.58785	0.61020	0.61165
City weather	x	x	x	x	x	
Holidays	x	x	x	x		
Fixed effects:						
Contract	x	x	x	x	x	x
Contract by month of year	x	x	x	x	x	x
Contract by day of week	x	x	x	x	x	x
Day of week by month of year	x	x	x	x	x	x
Month			x			
Month by city				x		
Day					x	
Day by city						x

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Two-way clustering: city level and month level. For columns 4 and 5.
The two-way clustering is at the city and day level.

Notes: Log-log OLS regressions, robust standard errors clustered at the city and day level in parentheses. The dependent variable is the daily total electricity consumption in kWh of contract i in period t. p_{it} is the daily total marginal price of contract i in period t. Lockdown area is a factorial of COVID-related restrictions. COV ID measures index is a continuous index capturing the lockdown severity varying at the town and daily levels. City weather is a vector of weather controls. Holidays is a national holiday indicator. All regressions control for contract, contract-by-moy, contract-by-dow, dow-by-moy FE, city weather, and holidays. In addition, the regression under column (3) controls for month FE, the one under column (3) controls for month-by-city FE. Two-way clustering: city level and month of sample level. For columns 4 and 5.

Table B.2: Daily Analysis - 2SLS

2SLS	$ln(y_{it})$					
	(1)	(2)	(3)	(4)	(5)	(6)
$ln(p_{it})$	-0.12067***	-0.02675	-0.04954***	-0.05124***	-0.05021	-0.05124
	(0.0137)	(0.0262)	(0.0087)	(0.0117)	(0.0345)	(0.0348)
Lockdown area: White	0.02215					
	(0.0156)					
Lockdown area: Yellow	0.08242***					
	(0.0227)					
Lockdown area: Red	0.11589***					
	(0.0174)					
Covid measures index		0.00231***	0.00106***			
		(0.0004)	(0.0004)			
Observations	24,220,492	24,220,492	24,220,492	24,220,492	24,220,492	24,010,570
Adj. R^2	0.57902	0.58014	0.58321	0.58785	0.61020	0.61165
City weather	x	x	x	x	x	x
Holidays	x	x	x	x		
Fixed effects:						
Contract	x	x	x	x	x	x
Contract by month of year	x	x	x	x	x	x
Contract by day of week	x	x	x	x	x	x
Day of week by month of year	x	x	x	x	x	x
Month			x			
Month by city				x		
Day					x	
Day by city						x

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Two-way clustering: city level and month level. For columns 4 and 5.
The two-way clustering is on the city level and day level.

Notes: Log-log 2SLS regressions, robust standard errors clustered at the city and day level in parentheses. The dependent variable is the daily total electricity consumption in kWh of contract i in period t. p_{it} is the daily total marginal price of contract i in period t. Lockdown area is a factorial of COVID-related restrictions. $COVID$ measures index is a continuous index capturing the lockdown severity varying at the town and daily levels. $City$ weather is a vector of weather controls. Holidays is a national holiday indicator. All regressions control for contract, contract-by-moy, contract-by-dow, dow-by-moy FE, city weather, and holidays. In addition, the regression under column (3) controls for month FE, the one under column (3) controls for month-by-city FE. Two-way clustering: city level and month of sample level. For columns 4 and 5.

Table B.3: Weekend vs Weekdays - OLS

OLS	$ln(y_{it})$		
	(1)	(2)	(3)
$ln(p_{it})$ x $1(weekday_{it})$	-0.06383***	-0.02151**	-0.01615***
	(0.0073)	(0.0098)	(0.0039)
$ln(p_{it})$ x $1(weekend_{it})$	-0.06310***	-0.01972*	-0.01566***
	(0.0073)	(0.0108)	(0.0056)
Observations	24,220,492	24,220,492	24,220,492
Adj. R^2	0.57947	0.58017	0.58784
City weather	x	x	x
Holidays	x	x	x
Fixed effects:			
Contract	x	x	x
Contract by month of year	x	x	x
Contract by day of week	x	x	x
Day of week by month of year	x	x	x
Month by city			x
Lockdown area	x		
COVID measures index		x	

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Two-way clustering: city level and day level.

Notes: Log-log OLS regressions, robust standard errors clustered at the city and day level in parentheses. The dependent variable is the daily total electricity consumption in kWh of contract i in period t. p_{it} is the daily total marginal price of contract i in period t. It interacts with weekday and weekend. City weather is a vector of weather controls. Holidays is a national holiday indicator. Lockdown area is a factorial of COVID-related restrictions. COVID measures index is a continuous index capturing the lockdown severity varying at the town and daily levels. All regressions control for contract, contract-by-moy, contract-by-dow, dow-by-moy FE, city weather, and holidays. In addition, the regression under column (1) controls for lockdown areas, the one under column (2) controls for the COVID measures index, and the one under column (3) controls for month-by-city FE.

Multi-dimensional wellbeing of IAM scenarios: an assessment of the illustrative mitigation pathways of the IPCC 6th assessment report

Contribution to the EDITS project from the Synthesis WG: synthesizing the LEDM scenarios using a multi-dimensional framework

Elina Brutschin (IIASA), Shonali Pachauri (IIASA), Yannik Stuka (CMCC) and Massimo Tavoni (CMCC)

1. Approaches to evaluate scenarios

There is a growing body of literature that evaluates scenarios from different conceptual angles using a variety of methods. For example, scenarios have been evaluated from feasibility (Brutschin et al., 2021; Cherp et al., 2021; Gambhir et al., 2017) or plausibility (Pielke et al., 2022) perspectives, in terms of their general alignment with historical trends (Semieniuk et al., 2021; van Sluisveld et al., 2015; C. Wilson & Grubler, 2011), expert opinions (Grant et al., 2021; van Sluisveld et al., 2018), and bottom-up assessments from other models or literature reviews (Creutzig et al., 2021; Warszawski et al., 2021). The essence of the approach of ***scenario evaluation lies in taking scenario output and benchmarking it to a certain line of evidence***.

It is widely acknowledged in climate debates that political support for certain mitigation actions will depend not only on technological feasibility or the capacity of states to implement certain policies but also on whether certain mitigation options are widely accepted. There are now growing calls in the literature to also undertake more normatively informed evaluations of scenarios with a broader focus on justice issues (Rubiano Rivadeneira & Carton, 2022; Zimm et al., under review). If these concerns are not directly addressed, there is a danger that climate mitigation scenarios may be criticized and ambitious climate mitigation discredited (Lamb et al., 2020; Tollefson, 2015).

Some scholars have argued for a separation of the concepts of feasibility and desirability when evaluating scenarios (Brutschin et al., 2021; Jewell & Cherp, 2020). This allows for a better conceptual understanding of what lies within the capacity of actors (feasibility) and what might depend on more normative goals (desirability) such as for example Sustainable Development Goals (SDGs). One key way to evaluate scenarios from a desirability perspective is to focus on indicators that go beyond simple GDP measures, and include a broader understanding of individual ***well-being*** (Emmerling et al., 2021), especially in energy and climate debates (Rao & Wilson, 2022). This poses a number of challenges given that most climate mitigation scenarios focus on techno-economic processes and model regions at a highly aggregated level. These models do not typically include or report assumptions about individual consumption or that of certain population groups (such as those distinguished by income or gender) explicitly. Additionally, the concept of wellbeing is multidimensional and there are many different ways to operationalize it.

This report advances existing knowledge and methodology outlined in literature by introducing a novel framework to assess scenarios generated by Integrated Assessment Models (IAMs) from a ***wellbeing perspective***. We first draw on theoretical and empirical insights from literature to develop our framework, and then employ a selection of illustrative scenarios and indicators to apply it.

1.1 General well-being concept

The concept of wellbeing is ***multidimensional*** and has been used in various fields of research, applying a wide variety of methods and approaches (Lijadi, 2018). Generally, the main goal of wellbeing studies is to identify measures that would allow comparison across ***cultural context*** and ***time*** on whether ***quality of life*** is improving or not, and requires specifying ***whose*** wellbeing is being assessed and in ***which areas of life*** (Levy & Guttman, 1975). Several countries (Canada, Department of Finance, 2021; New Zealand, Treasury, 2023; UK Office for National Statistics, 2023) have in recent years made efforts to develop measurement frameworks and define indicators to track and report on wellbeing and quality of life domains. While specific frameworks differ across countries, there

is growing consensus on a broad set of indicators that capture key aspects of well-being. Initiatives such as the OECD's Well-Being framework (OECD, 2020) and metrics developed to track progress towards meeting the United Nations' 17 Sustainable Development Goals (SDGs) have also helped encourage consistency. However, there is still a lack of consensus on which indicators should be used in research and in a broader policy context.

One of the main discussions revolves around the distinction between ***subjective (hedonic)*** and ***objective wellbeing (eudaimonic)*** (Lamb & Steinberger, 2017; Voukelatou et al., 2021). Subjective wellbeing can be measured through surveys by asking people about their general level of satisfaction, while objective wellbeing can be proxied by various country level indicators that capture different determinants of quality of life. Because it is challenging to gather comparable country level data from surveys, research has mostly focused on developing conceptual frameworks and indicators of objective wellbeing. The major drawback of this is, however, that by omitting to focus on subjective wellbeing, results might not be comparable across time and cultural context (Lutz et al., 2021). Some of the challenges with using objective wellbeing indicators can be illustrated by the measure of income, which is still one of the dominant measures of general welfare. (Easterlin et al., 2010, p. 22463) for example has shown that "at a point in time both among and within nations, happiness varies directly with income, but over time, happiness does not increase when a country's income increases". (Mikucka et al., 2017) argue that economic growth has a positive effect on subjective wellbeing only if it is associated with increasing social trust and declining income inequality.

In the absence of comparable surveys for most regions, studies that are focused on tracking impacts of certain policies on subjective wellbeing might still need to rely on other, more easily accessible indicators at the country level. Nonetheless, a useful strategy can be to continue efforts to try to understand which country level indicators are among the best predictors of subjective wellbeing, as it has been shown that there is generally a high correlation between indicators of subjective and objective wellbeing (Morrison et al., 2011). We thus might need to rely on proxies of subjective wellbeing. For instance, there is growing evidence that institutional environment is one of the more robust predictors of subjective wellbeing (Emmerling et al., 2021; Helliwell et al., 2018), as it affects many key areas such as economic performance and security that in turn affect subjective wellbeing.

Which ***dimensions*** of wellbeing should be considered has also motivated a substantial body of research (Alkire, 2002). Overall, many studies are in agreement that indicators pertaining to health and survival are among the most important ones (Alkire, 2002; Lutz et al., 2021). Akin to the wide array of concepts and measurement frameworks to capture wellbeing, there is also a growing effort to capture the multidimensionality of poverty (Pachauri & Rao, 2020) and develop indicators that go beyond simple measures of income at the country level to track poverty. Such multidimensional poverty approaches focus on access to and the distribution of key infrastructures and services. In this report, rather than proposing a new measurement framework of wellbeing, we are interested in developing a useful concept that would allow for a more systematic comparison and evaluation of climate scenario outputs along specific wellbeing domains. In Section 1.2 we discuss in more detail the concept of wellbeing in the context of climate mitigation.

1.2 Wellbeing in the context of climate change mitigation

There is a growing interest to focus on the concept of wellbeing when thinking about future mitigation strategies

(Dodds, 1997; Emmerling et al., 2021; Lamb & Steinberger, 2017; Lutz et al., 2021). The discussion is centered around the economic and social impacts of climate mitigation policies and actions. Of particular interest are the impacts of energy transitions on employment and equity, particularly on the costs for the poorest groups within society. In addition, how certain technologies might affect the environment and natural resources, such as biodiversity, water quantity and quality, and other concepts of interest can be assessed. On the opposite side, an evaluation of possible (health) impacts if there is *no* mitigation and how global warming might affect the most vulnerable groups can also be important to consider.

One of the main linkages between wellbeing and GHGs is through ***energy needs and consumption*** patterns, which are modeled in IAMs through the agricultural and energy sectors (Lamb & Steinberger, 2017; Millward-Hopkins et al., 2020; Steinberger & Roberts, 2010). Many regions in the world still do not have access to basic needs (Kikstra et al., 2021) and are considered to have lower levels of wellbeing (Emmerling et al., 2021). Studies show that a major economic growth in the Global South assuming patterns observed in the past would lead to emissions levels that would exhaust the global 2°C carbon budget (Lamb & Rao, 2015). On the other hand, other indicators of development, such as focus on satisfying basic needs and access to services (Rao & Baer, 2012), rather than just economic growth, and a more equal distribution of consumption patterns, are more aligned with ambitious climate mitigation scenarios and lower global energy demand (Kikstra et al., 2021; Lamb & Rao, 2015; Millward-Hopkins et al., 2020).

There is a growing movement to integrate the concept of wellbeing into climate mitigation scenarios. Emmerling et al. (2021) have projected a subjective wellbeing indicator from the World Values Survey onto Shared Socioeconomic Pathways (SSPs), revealing major differences for certain regions. Lamb and Rao (2015) have extrapolated Human Development Index (HDI) trends into the future, assessing their impact on GHGs. Meanwhile, Moyer and Bohl (2019) argue that scenarios assuming lower demands due to behavioral changes, such as lifestyle change scenarios, compare less favorably to other mitigation strategies along key Sustainable Development Goals (SDGs). However, their results may be limited by inadequate measures of economic welfare and access to services. Fujimori et al. (2020) have developed a metric to assess the implications of CO2 reduction on some of the key SDG indicators, finding that "1% reduction of CO2 can avoid 0.57% of air pollution-related premature deaths" in Asia. Despite these efforts, a simple conceptual framework that would allow for a systematic comparison of scenarios to trace and evaluate multiple trade-offs and benefits of different mitigation strategies from a wellbeing perspective is still missing.

1.3 Proposed Framework

Given our objective of developing a framework that facilitates a more systematic comparison of climate scenarios, and building on the preceding discussion, we propose a framework that covers critical dimensions and employs a limited number of indicators. A primary criticism of current wellbeing frameworks is their excessive complexity, featuring too many indicators and making it challenging to obtain a broader overview (Lutz et al., 2021; Pongiglione, 2015). Accordingly, we intentionally focus on key dimensions identified in prior literature and only incorporate a few indicators.

Figure 1 provides an overview of our conceptual framework, which identifies three essential dimensions of

wellbeing: health, decent living, and security and stability. These dimensions are well-established in the existing research on wellbeing (Levy & Guttman, 1975) and are closely linked to significant consumption patterns in the energy and agricultural sectors. They can also be effectively assessed within the context of Integrated Assessment Model (IAM) scenarios. The overall conceptual framework also links different levels of analysis, including global, state, and individual levels.

While an ideal wellbeing framework would enable comparisons across individuals or specific groups, such as gender, age, or income, scenario data is typically only available as regional averages. Therefore, we can only evaluate differences across regions and track convergence. Nonetheless, this can enable us to assess some of the observed patterns from a justice perspective, depending on the regional trajectories assumed or reported by scenarios (interregional equality). In case scenarios report distributions by key socio-economic groups or countries, a more nuanced analysis from the justice perspective could also be possible (intrastate equality).

Our first proposed dimension of wellbeing is health, which is directly affected by climate impacts through several channels, including emission levels and air pollution, water access and quality, and the impact of global warming on the environment and temperature (Fischer & Van de Vliert, 2011; Souza-Jr., 2022). ***Air pollution***, which has been shown to be linked to life satisfaction (Welsch, 2006), can be used as a key indicator in this context, and its effects on mortality and morbidity rates can be proxied for a given scenario (Fujimori et al., 2020). To this end, the global atmospheric source-receptor model TM5-FASST(R) (a modified version of TM5-FASST that uses several mortality functions) is used to calculate mortalities for different scenarios and regional aggregations (Van Dingenen et al., 2018). Additionally, the impacts of global warming, natural disasters, and extreme weather events (Adeagbo et al., 2016; Ahmadiani & Ferreira, 2021; Yang et al., 2018) can also be assessed when comparing different temperature goals.

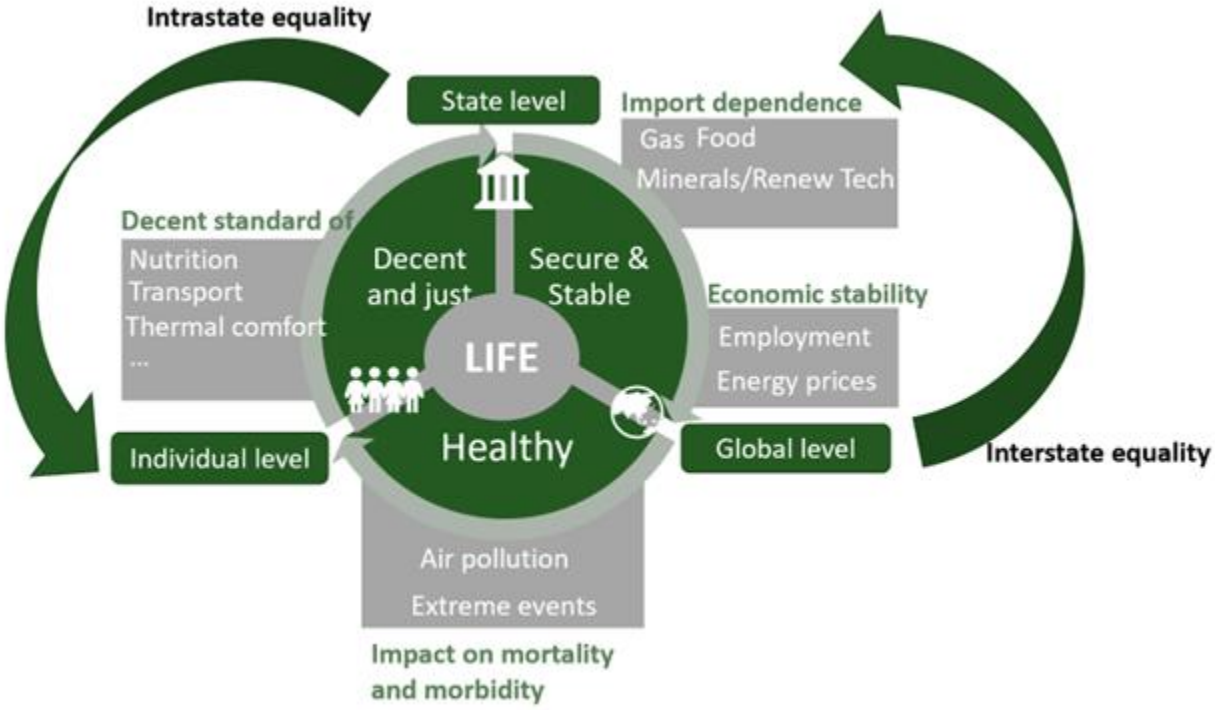

Figure 1. The proposed conceptual framework that can be used for scenario evaluation from the wellbeing perspective.

Instead of relying on traditional economic measures of wellbeing, our proposed framework emphasizes access to essential services and builds on the concept of ***decent living standards*** (Rao et al., 2019), which recognizes the critical link between energy, service provision, and wellbeing (Rao & Wilson, 2021). This approach aligns with the growing calls to move beyond income-based poverty measures (FitzRoy et al., 2012). Furthermore, recent research has suggested that individual GHG emission levels do not necessarily correlate with wellbeing, as individuals with high-emission lifestyles do not necessarily report higher levels of health or happiness (Roberts et al., 2020; Wilson et al., 2013). These findings reinforce the need to explore alternative lifestyles and to consider consumption patterns and how these link to specific services. While the decent living framework encompasses a wide range of indicators, we focus on ***mobility patterns, energy consumption in residential and commercial buildings, and food intake*** as key indicators, as they represent significant sources of GHG emissions. In particular, the role of nutrition as a key mitigation lever (Bajželj et al., 2014; Soergel et al., 2021) has received limited attention thus far.

Lastly, we suggest examining the ***security dimension*** by analyzing trade patterns of key resources and evaluating the employment shifts that result from different mitigation strategies within the energy sector. For instance, ***trade dependencies*** can be assessed in energy scenarios from an energy security standpoint (Jewell et al., 2014), and the technology variables reported in these scenarios can be used to approximate ***employment shifts*** in a given region (Pai et al., 2021). This analysis can be complemented by an investigation of ***energy diversity*** and hence security based on the number of different fuel types drawn on in different scenarios at different levels of aggregation. Table

1 translates this proposed framework into indicators that can be applied in the context of IAMs.

Indicator	***Notes***
Dimension: Health	
Mortality due to Air Pollution	# of Deaths
Dimension: Decent Living Standards	
Transport	*Service provision in pkm per capita per year*
Buildings	*Floor space per capita in sqm*
Food intake	*kCal/capita/day*
Dimension: Secure and Stable	
Energy Intensity	MJ/$GDP
Absolute yearly volumes of imported oil & gas	EJ/year
Employment Shifts in the Energy Sector	# of people employed
Energy Diversity	Shannon Diversity Index

Table 1. The proposed indicators for scenario evaluation from a wellbeing perspective.

2. IAM scenarios

2.1 General description

Integrated Assessment Models (IAMs) are models that link representations of the global economy, energy, and land-use systems using various assumptions (Krey, 2014). These models are valuable tools for identifying "solution spaces" to achieve ambitious climate targets and are influential in promoting and shaping scientific and policy discussions. The newly released database of global IAM scenarios following the publication of the IPCC Sixth Assessment Report (AR6) (Byers et al., 2022) provides an opportunity to explore the proposed wellbeing framework and assess scenarios from this perspective.

2.2 Select Scenarios

To explore possible insights when using our framework, we apply it to the illustrative mitigation pathways from the AR6 database (Byers, Edward et al., 2022). We focus on a set of scenarios that allows for comparison across different narratives such as continuation of current policies and ambitious climate mitigation scenarios (see Table 2). Our focus is first on the low demand scenario (LED) developed by Grubler et al. (2018), which assumes rapid technological development and behavioral change resulting in significant global demand reduction. The Sustainable Development Scenario (SDP) developed by Soergel et al. (2021) within the REMIND modeling framework assumes the achievement of many of the Sustainable Development Goals (SDGs).

Acronym	***Scenario***	***Climate Category***	***Narrative***	***Reference***
Illustrative Pathway				
ModAct	IMAGE 3.0 - EN_INDCi2030_3000f	C6	Moderate Action	Riahi et al. (2021)
Illustrative Mitigation Pathways				
GS	WITCH 5.0 - CO_Bridge	C3	Less rapid introduction of mitigation measures followed by a subsequent gradual strengthening	van Soest et al. (2021)
Neg	COFFEE 1.1 - EN_NPi2020_400f_lowBECCS	C2	Heavy reliance on carbon dioxide removal that results in net negative global GHG emissions	Riahi et al. (2021)
Ren	REMIND-MAgPIE 2.1-4.3 - DeepElec_SSP2_ HighRE_Budg900	C1	Rapid deployment and technology development of renewables	Luderer et al. (2022)
LD	MESSAGEix-GLOBIOM 1.0 - LowEnergyDemand_1.3_IPCC	C1	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	Grubler et al. (2018)
SP	REMIND-MAgPIE 2.1-4.2 - SusDev_SDP-PkBudg1000	C1	Sustainable development. including reduced inequality and deep GHG emissions reduction	Soergel et al. (2021)

Table 2. Illustrative Mitigation Pathways.

Figure 2 shows that the LED and SDP scenarios are mostly aligned in terms of regional final energy per capita trajectories, especially in the developed regions (OECD90+EU). However, there are major differences reported in

terms of final energy per capita in the developing regions of Asia, Latin America (LAM), and Middle East and Africa (MAF). In 2050, the levels of final energy per capita in these regions are substantially lower compared to 2020 in the LED scenario as compared to in the SDP. Nevertheless, this does not imply that the levels of service provision in the developing regions are declining in the LED scenario.

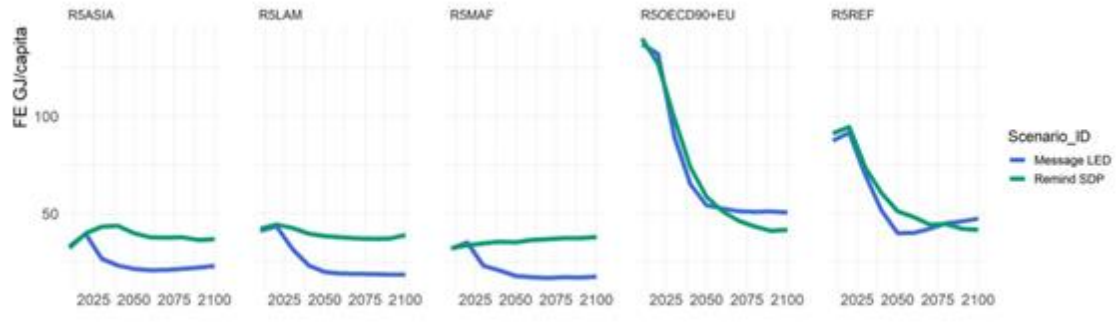

Figure 2. Final Energy per capita across five IAM regions. Comparing Low Energy demand scenario from the MESSAGE model (Grubler et al. 2018) with SDP from the REMIND model (Soergel et al. 2021). Scenario data from Byers et al. (2022).

In Figure 3, we highlight the difference in the service provision indicator for mobility. LED assumes major improvements in terms of mobility services in all regions, while SDP assumes a pattern that resembles regional convergence more closely. This indicates a significant difference between LED and SDP in terms of technological improvement assumptions, with LED assuming much faster energy efficiency improvements and technological spillovers. Furthermore, this example underscores the importance of scrutinizing scenario assumptions that extend beyond the reported levels of final energy per capita. Merely contrasting reported final energy scenario data can be deceptive, as it disregards the broader set of assumptions that were used to develop a given scenario narrative.

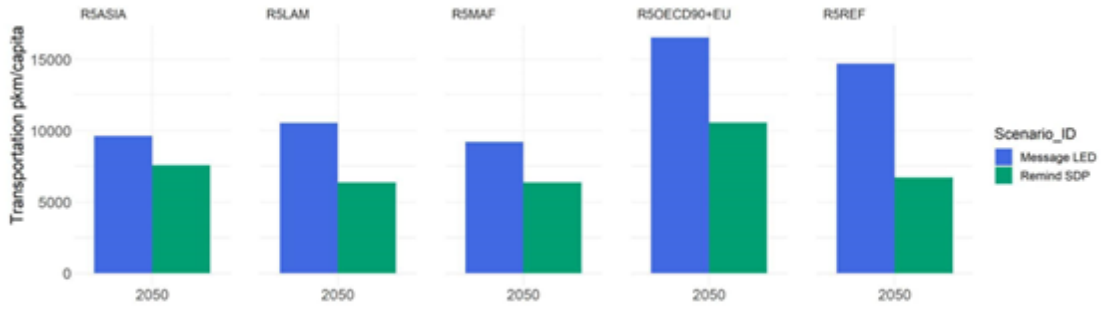

Figure 3. Implications for Mobility services. Reported Energy Service Transportation in Passenger Kilometers per capita. Scenario data from Byers et al. (2022).

3. Wellbeing Assessment

In the upcoming sections, we will focus on the chosen scenarios that were previously discussed in section 2.2. We will evaluate these scenarios based on the indicators that pertain to the dimensions introduced in Table 1.

3.1. Overview

Figure 4 shows a summary of the assessed dimensions and scenarios for the years 2030 and 2050. We trace that there is no clear mitigation option that stands out distinctively from a wellbeing perspective in these dimensions. We can observe heterogeneity in the results across two dimensions. Firstly, within a given year, a particular scenario might fare well in one wellbeing dimension but not necessarily in the other ones. A trade-off seems to emerge between certain wellbeing perspectives that urges for a careful balance to be found between the various indicators. Next, a given senario might exhibit great variation between the years 2030 and 2050 even for the same assessed dimension. Having performed well in 2030 in one aspect of wellbeing does not predict equally well performance in 2050. This feature describes the time dependent mechanism of wellbeing indicators for the scenarios, stating how certain equilibrium levels might only be reached in the long-run and short-term achievements as well as deficits might be diluted as time goes by. This poses difficulties for policy-making as agents need to balance gains in the short-run with potentially adverse developments in later periods and vice versa. In the next sections we will dive into these indicators individually and explore how the scenarios compare on a more granular wellbeing level.

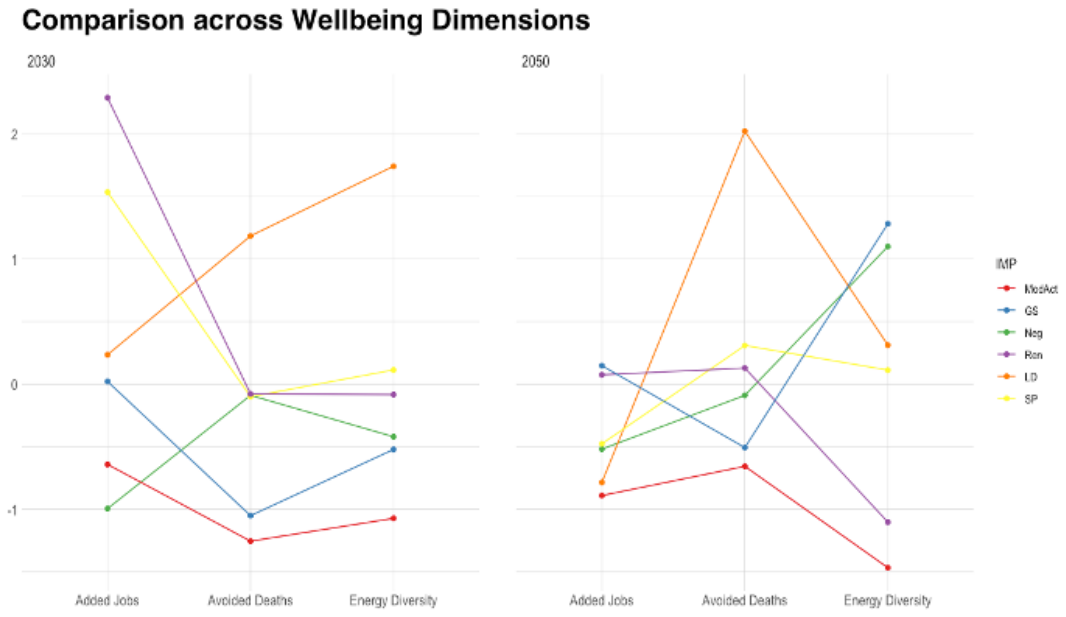

Figure 4. Comparison across Wellbeing Dimensions. For Neg Avoided Deaths is Median of other IMPs due to Data Unavailability.

3.2. Health

3.2.1 Methodology

Health is fiercely affected by Air Pollution levels. The latter has been shown to be causing respiratory illness and deaths in a variety of studies (..). We draw on the R-based global atmospheric source–receptor model FASST for rapid impact analysis of emission changes on air quality and short-lived climate pollutants (Van Dingenen et al., 2018). Providing this model with the Emission Predictions of the selected IMPs yields premature deaths attributable to PM2.5 Air Pollution on the chosen R5 regional aggregation under 60 different specifications of impact functions for the years 2020, 2030, and 2050. The impact functions parameterize the effect of air pollution on mortality in different ways and thus provide slightly differing results. Finally, baseline scenarios are identified for each IMP and respective premature deaths are calculated with the FASST-R model as well for these. Importantly, these baselines are chosen within the same Model family that the IMP pertains to in order to account for heterogeneous model assumptions that can lead to imprecise comparisons between scenarios. These baselines are then used to calculate the premature deaths avoided within the respective IMP scenario with respect to such a BAU Scenario.

3.2.2 Results

Figure 5 shows the avoided premature deaths of the IMPs with respect to their model baseline scenario. Note that the *COFFEE* model from which the *Neg* IMP comes does not produce results in FASST-R and is thus excluded from the display. A couple of characteristics can be inferred from the graphs. First, the bulk of deaths can be avoided in Asia according to this model run. This region covers by far the largest share of health benefits in all scenarios and time stamps, except for *ModAct* in 2030, where only slight differences with regard to the baseline run occur. Next, the scenarios in itself display vastly different health benefit potential. Pathways aiming for a lower temperature increase achieve lower deaths related to outdoor PM2.5 Air Pollution compared to those with weaker mitigation aims. *LD* fares best in both time stamps and may avoid on average around one million deaths in 2030 and 1.3 million deaths in 2050. The error bars represent the standard deviation of this projection. Lastly, it can be observed how over time the benefit accumulates as more avoided deaths in more distant periods, thus showing the positive long-term effect of ambitious mitigation scenarios. Figure 6 plots the average avoided deaths for each scenario on a world map over two time periods.

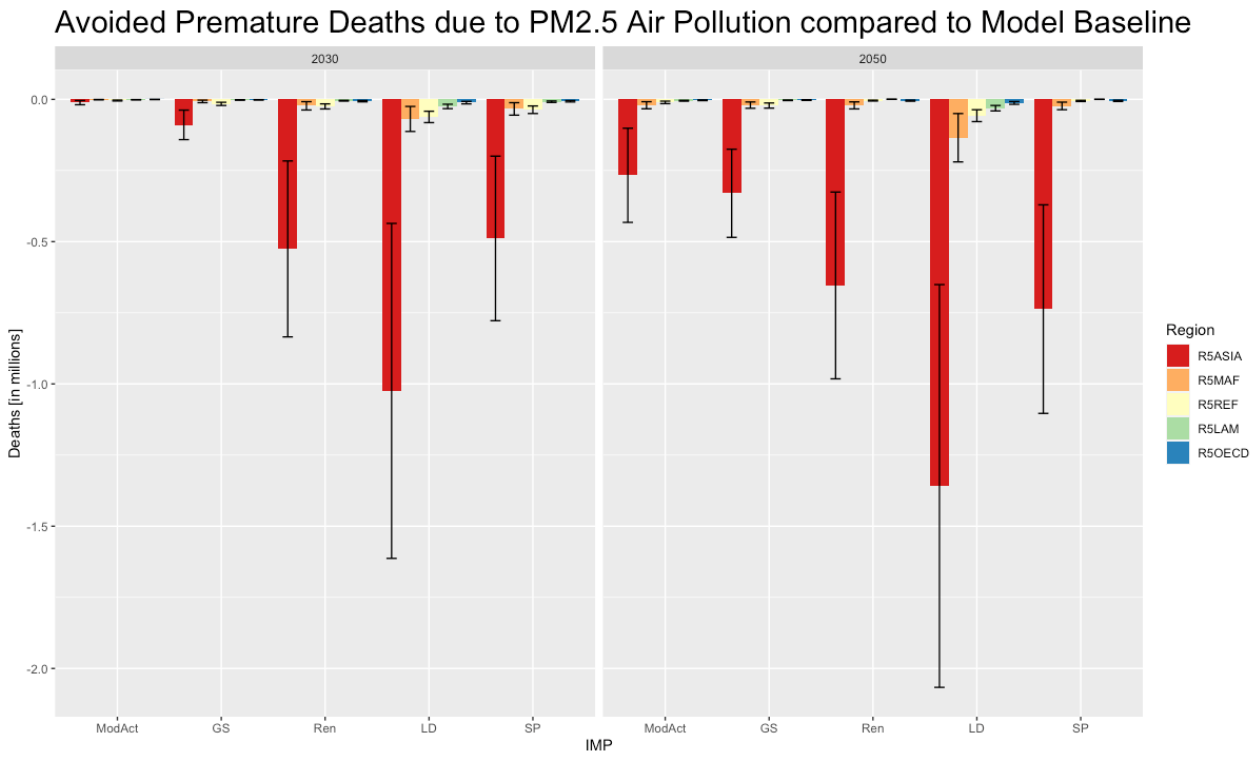

Figure 5. Avoided Premature Deaths due to PM2.5 Air Pollution compared to Model Baseline. The bars represent the range obtained using different mortality functions.

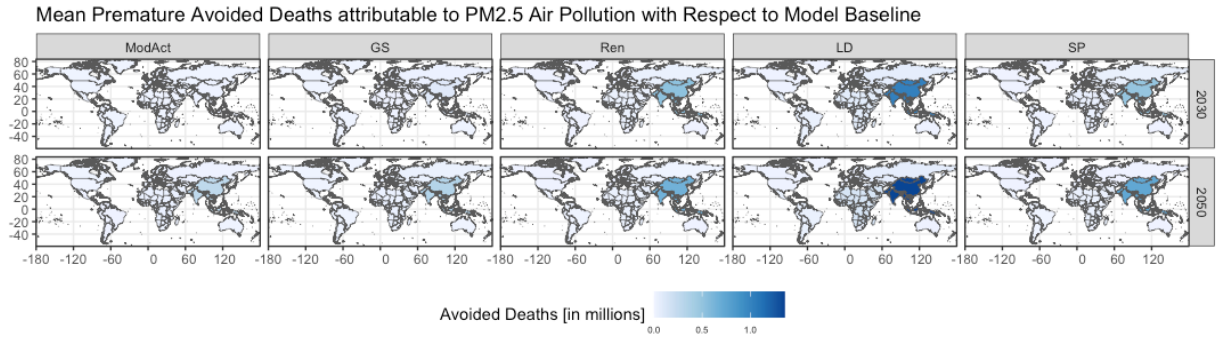

Figure 6. Mean Premature Avoided Deaths attributable to PM2.5 Air Pollution with Respect to Model Baseline.

3.3. Decent Living Standards

In Section 1.2, the literature suggests that wellbeing is not monotonically related to the consumption of material goods and services, and beyond some threshold, further consumption may not increase wellbeing and may even

lead to negative outcomes (Lamb & Steinberger, 2017). In line with this finding, Rao et al. (2019) propose a decent living standard that outlines a set of basic material and non-material needs that every individual should be able to achieve while staying within the planet's resource boundaries. These needs include access to basic services like clean water, sanitation, energy, education, healthcare, and communication, as well as access to food, housing, clothing, and transport that meet basic standards for a fulfilling life. Sufficiency thresholds have been established for each of these basic needs, and based on these thresholds, energy requirements have been calculated (Kikstra et al., 2021; Rao et al., 2019). This report will specifically focus on the energy and service provision levels related to the ***transport, buildings, and food sectors***, which are significant contributors to the increase of greenhouse gas emissions.

3.3.1 Transport

Figure 7 provides insights into the final energy consumption levels per capita in the transport sector, and if available, the passenger kilometers per capita. Passenger kilometers per capita is a crucial indicator for measuring the mobility patterns within a given region. While mobility patterns can be highly specific to the context and environment, Kikstra et al. (2021) establish mobility thresholds by using the transport system in Japan as a benchmark. They argue that the Japanese transport system is highly efficient and provides universal access to key transport services. In ***Panel 6A***, 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. As shown in ***Panel 6B***, this implies that there is regional convergence in the provision of mobility services around the decent living threshold in the SDP scenario.

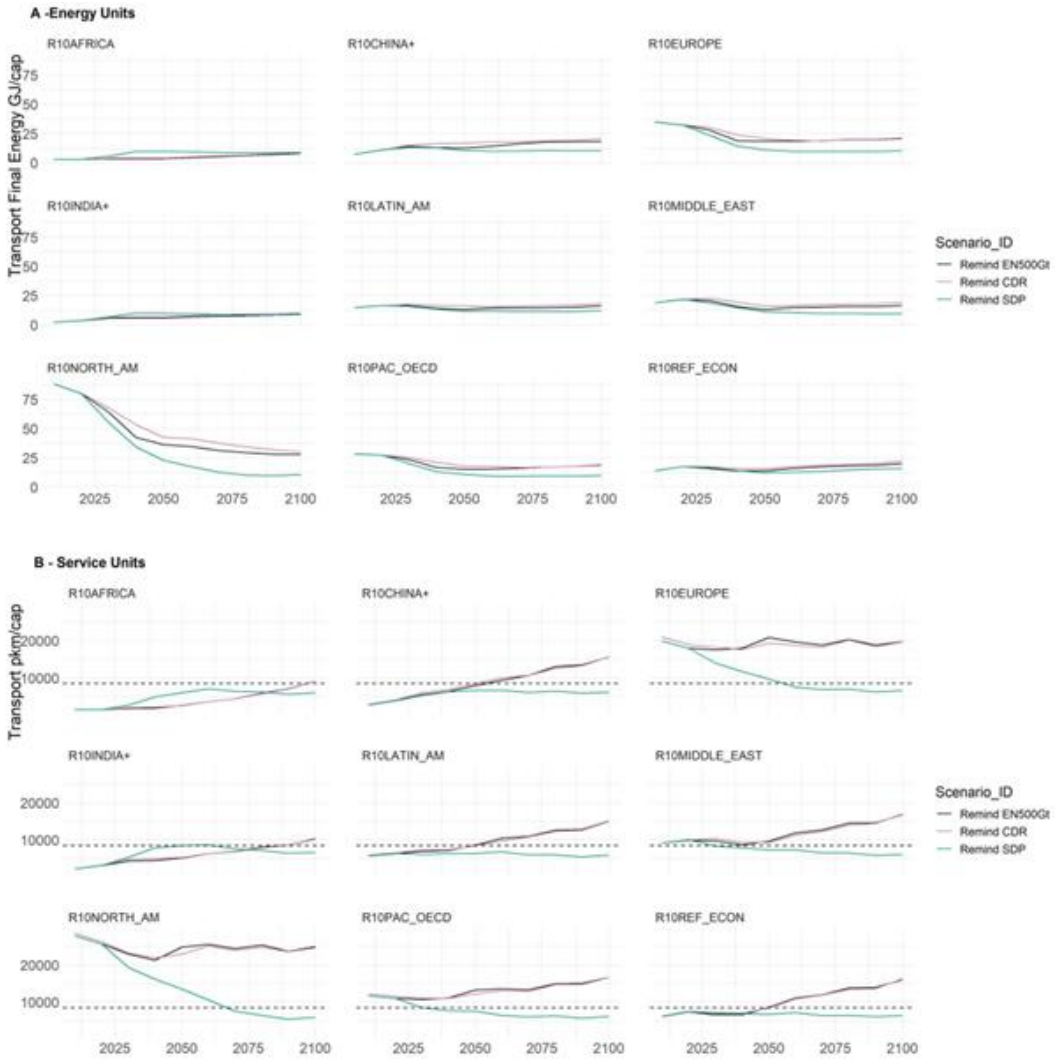

Figure 7. Trajectories in the transport sector in Energy (Panel A) and Service Units (Panel B). Scenario data from Byers et al. (2022). Dashed line shows the pkm/cap threshold for decent living as proposed in Kikstra et al. (2021).

3.3.2 Buildings

Figure 8 displays patterns that are similar to those observed in the transport sector. Specifically, the SDP scenario projects significant improvements in the energy efficiency of buildings, especially in developed countries, but also in China beyond 2050. Only the SDP scenario provides information on the assumed floor space in square meters, which is another crucial indicator for estimating the levels of service provision and consumption patterns in the building sector (Rao et al., 2019). In Panel 7B, 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.

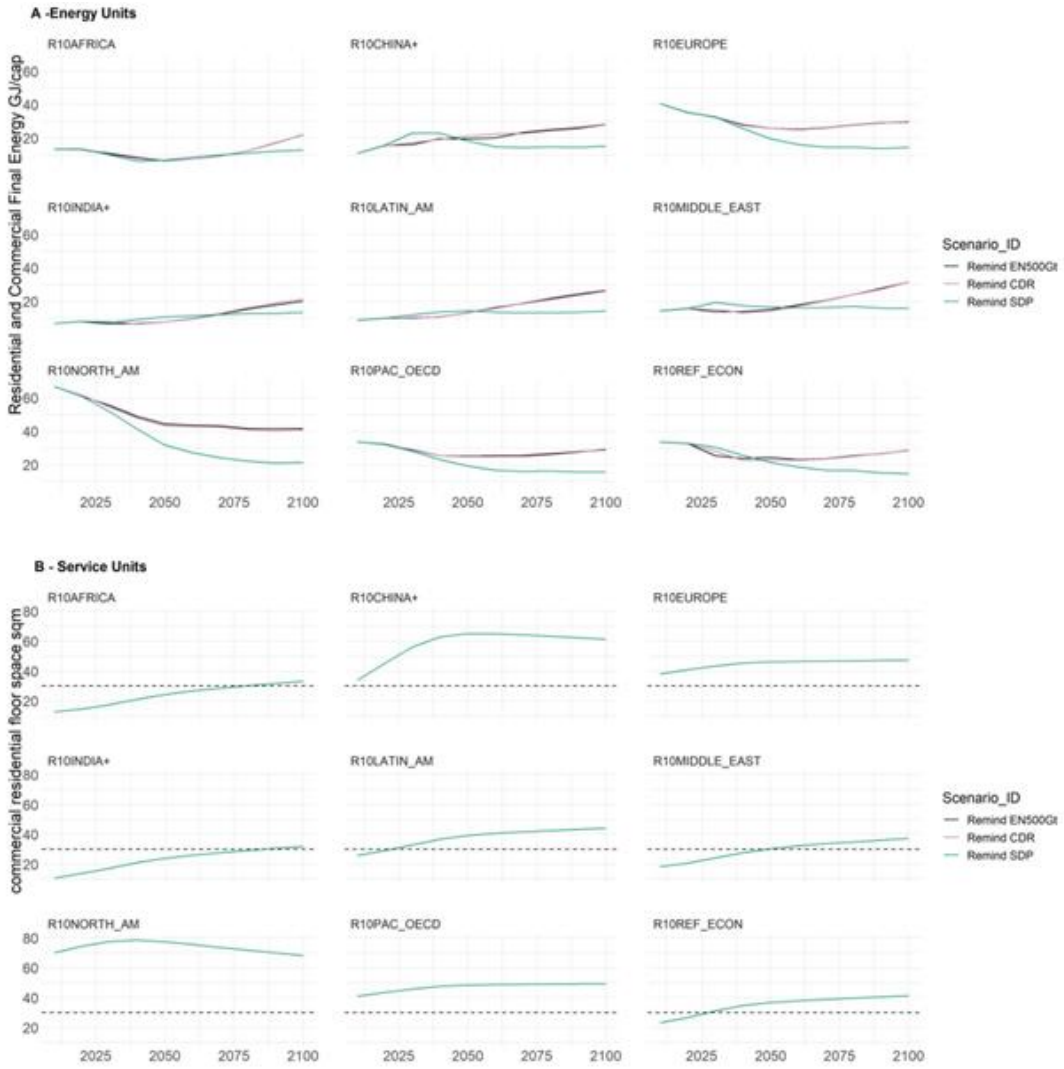

Figure 8. Trajectories in the building sector in Energy (Panel A) and Service Units (Panel B). Scenario data from Byers et al. (2022).

3.3.3 Food Intake

Recent estimates indicate that food systems are responsible for approximately one-third of global anthropogenic greenhouse gas emissions (Crippa et al., 2021). As a result, it is essential to examine consumption patterns to meet nutritional needs. Figure 9 provides insight into the assumed Food Demand in kcal per capita per day across the key scenarios. Unfortunately, the Net Zero scenario did not include this variable, making it difficult to make comparisons. However, we were able to compare the SDP with the CDR pathway.

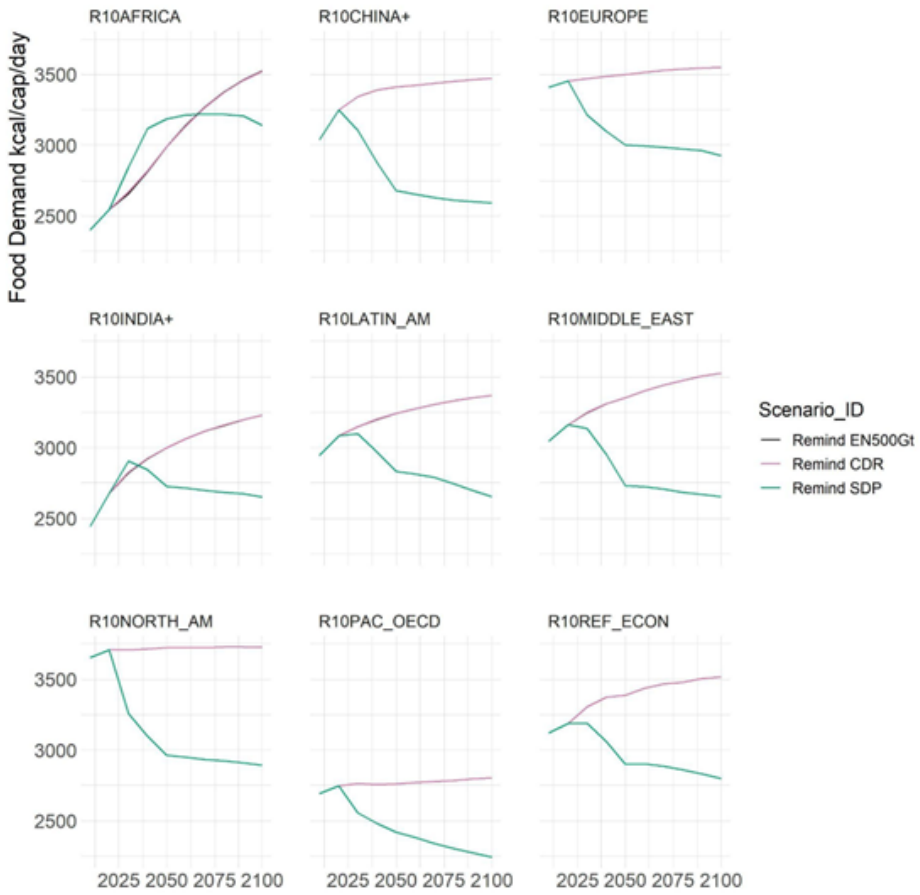

Figure 9. Trajectories - Food Consumption in kCal/capita/day. Scenario data from Byers et al. (2022).

From this comparison, it is clear that the SDP assumes a significant reduction in food consumption and waste, particularly in developed regions. Interestingly, the developing regions display noteworthy differences. For instance, the SDP scenario projects a more rapid increase in food demand for Africa than the CDR scenario. After 2050, there is either saturation or a further decline in food consumption across all regions. This insight highlights the critical role of food demand reductions as a lever for mitigation. By exploring the assumed consumption patterns in the SDP scenario, we can see that a substantial reduction in food demand across all regions could free up space for increased consumption in other sectors, while still enabling the achievement of the stringent mitigation goal of 1.5°C.

3.4. Security and Stability

In order to evaluate scenarios based on the dimension of security, we will refer to the energy security concept and previous research on energy security indicators for scenarios (Jewell et al., 2014). Jewell et al. (2014) propose using two types of indicators for energy security: resilience indicators, which measure the ability of a system to withstand

external shocks, and sovereignty indicators, which measure the degree to which a country or region is reliant on imports of critical technologies from other countries. To assess resilience, we will focus on energy intensity in MJ/$GDP, while to evaluate energy security from a sovereignty perspective, we will concentrate on trade dependence for oil and gas imports in a given region. Complementary to this analysis is an analysis of the energy diversity and the added jobs for each scenario.

3.4.1 Energy Intensity

In ***Figure 10***, we report energy intensity levels for three Remind scenarios (see section 2.2) for ten key IAM regions. We can clearly trace that the SDP scenario follows a path that would lead to more resilient energy systems in all regions. All scenarios lead to energy intensity improvements in all regions and there is not much difference between the Net Zero scenario and the CDR scenario. Notably, the SDP scenario displays significant energy intensity improvements in the Reformed Economies region, enhancing their energy system resilience considerably.

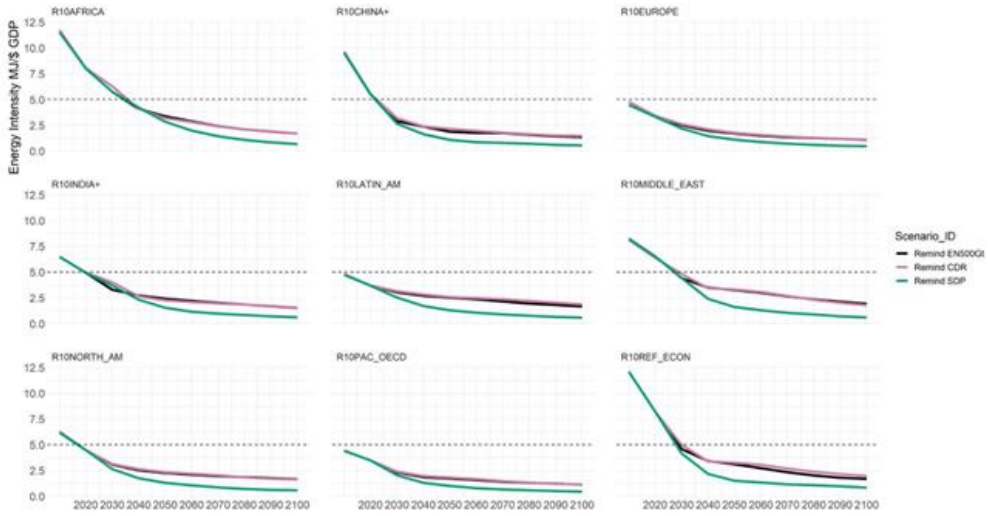

Figure 10. Energy Intensity trajectories for key scenarios. The dashed line indicates the level of energy intensity in Europe to highlight how far away other regions are from the levels reached in Europe. Scenario data from Byers et al. (2022).

3.4.2 Trade Dependence

In ***Figure 11*** we shift our focus to the trade dependence for oil and gas in crucial importing regions, namely China, Europe, and India. Figure 5A demonstrates the trade volume for oil in EJ/year, indicating that implementing low demand policies while following the SDP pathway would substantially decrease oil dependence in China and Europe. Conversely, while India initially experiences a trade volume increase, it rapidly declines around mid-century. In Figure 5B, we trace the assumed developments in terms of gas dependence. The results reveal a less distinct trend; 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. Moreover, the CDR pathway assumes a substantial increase in gas import dependence for India. 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.

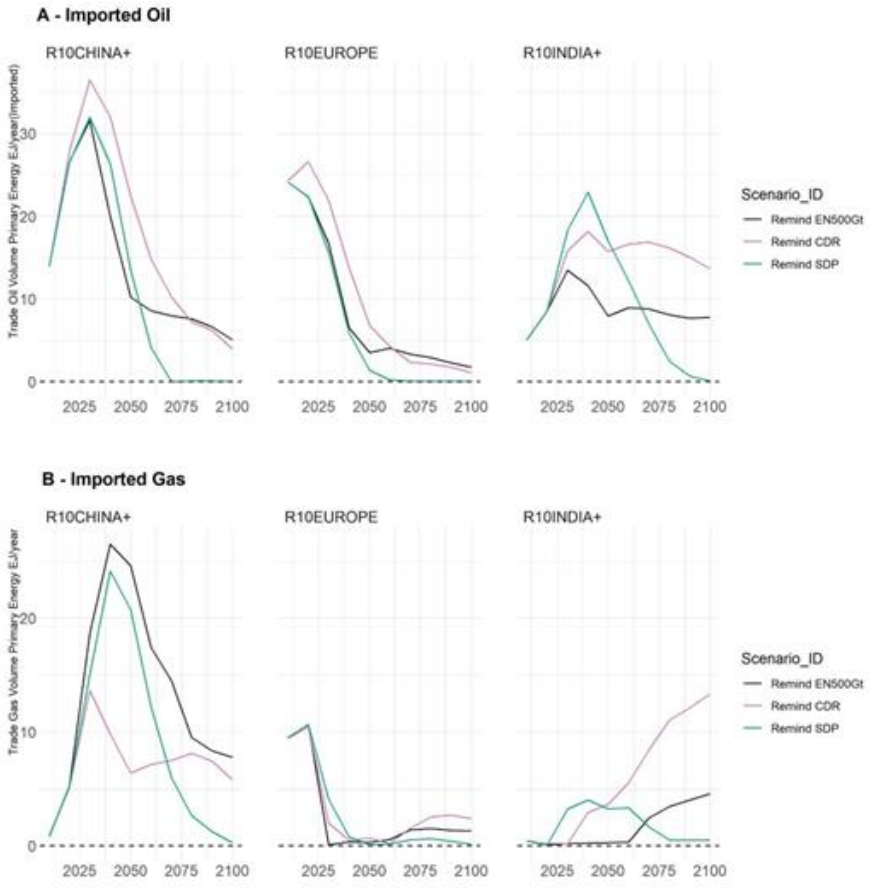

Figure 11. Oil and Gas Dependence across different narratives. Reported is Trade Oil/Gas Volume in EJ/year. Scenario data from Byers et al. (2022).

3.4.3 Energy Diversity

For this indicator, the Primary Energy Projections for the available fuels are extracted from the model outputs. Then, the Shannon Diversity Index is calculated at each time period with the given energy capacities. Figure 12 displays the results of this exercise. A puzzle that emerges is how scenarios with the highest diversity indices in the long run are a "middle of the road" kind. An explanation for this can be that *no mitigation/ current policy* scenarios (ModAct) stick to a mostly fossil fuel-based energy production, whereas scenarios at the top end of mitigation ambitions shift their energy supply almost entirely to renewables (Ren, LD, SP). These two types of pathways thus end up having no high diversity in their fuel production as they either keep relying on few energy sources or shift their supply to equally few renewables. Scenarios that incorporate renewables to a certain extent but keep relying on fossil fuels have the highest energy diversity indices as their distinct economies relies on the most diverse fuel

mix (GS, Neg)(cf. also Figure 13). It is to be noted however, that although high mitigation pathways have similar energy diversity indices to fossil-based scenarios on the other end of the spectrum, they still might be preferable as their energy supply, although not diverse, relying mostly on renewables, is much less import dependent than their fossil fuel counterpart.

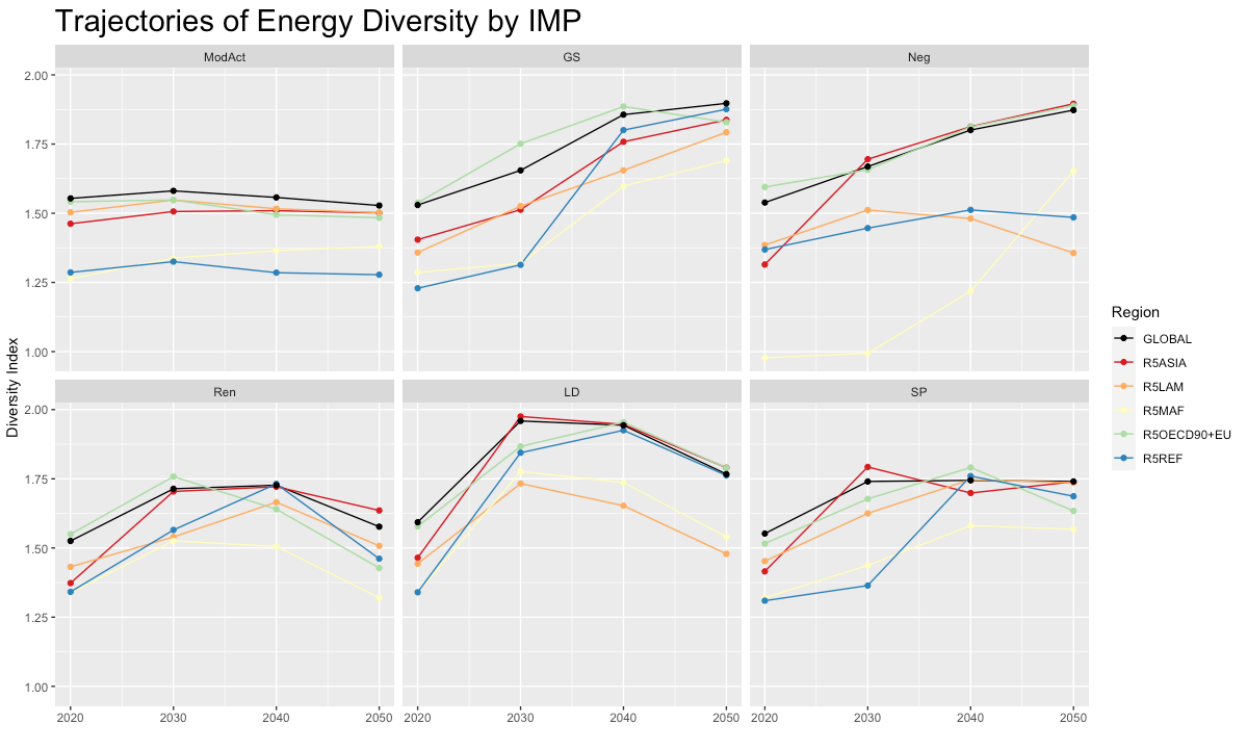

Figure 12. Trajectories of Energy Diversity per IMP calculated with Shannon Diversity Index.

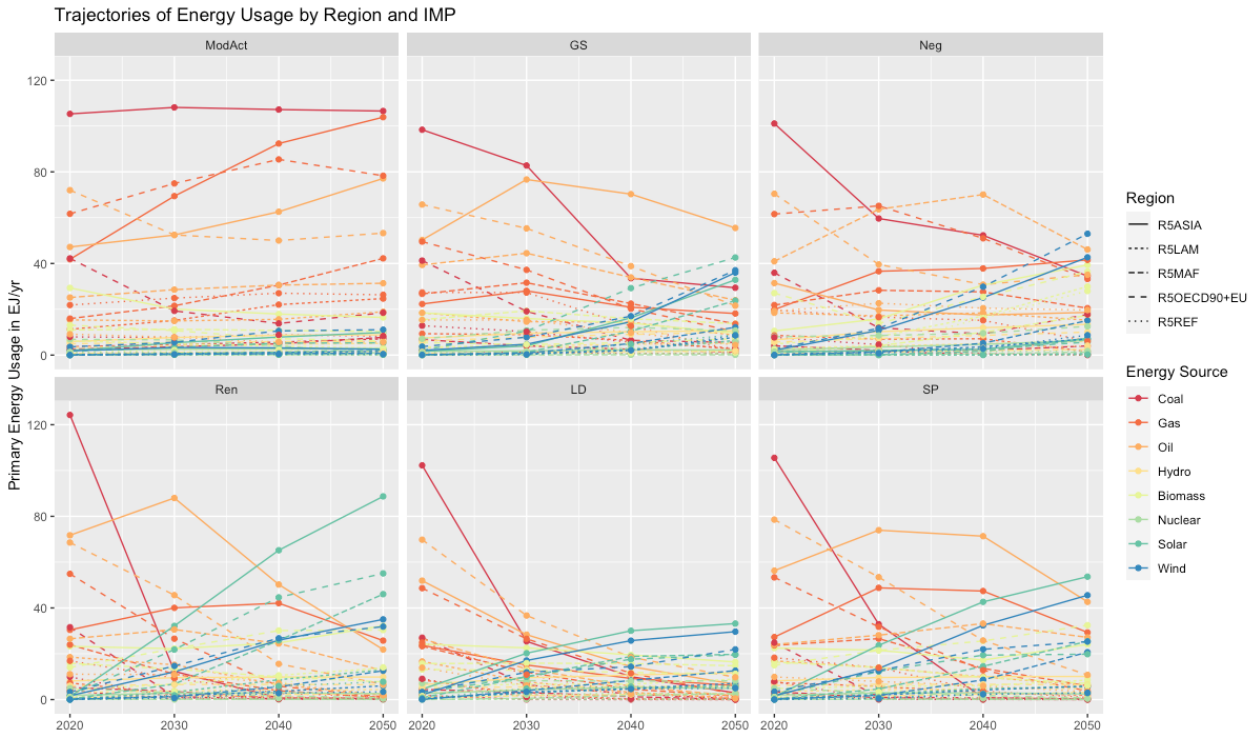

Figure 13. Trajectories of Energy Usage by Region and IMP.

3.4.4 Employment

3.4.4.1 Methodology

To calculate employment numbers from the scenario reporting, we draw on a job intensity matrix that details how many jobs are needed for each unit of energy in five job categories and for eleven fuel types at ISO3 level that has been developed by Pai et al. (2021) (Figure 14). These job intensities are then aggregated at the regional R5 level. Table 3 displays the scenario variables that adhere to the job categories in Figure 14. The table also shows that these variables however are not included homogenesouly in all the IMPs that were chosen for analysis. These missing data points, that are marked with coherent color coding and numbering from 1 to 3 will be recovered below and we will recap the procedure for each of them.

Job categories	Coal	Gas	Oil	Nuclear	Hydropower	Solar (PV)	Solar (CSP)	Traditional biofuels	Wind (onshore)	Wind (offshore)	Solid biomass
Construction and installation	X	X	X	X	X	X	X	–	X	X	X
Manufacturing	X	X	X	X	X	X	X	–	X	X	X
O&M	X	X	X	X	X	X	X	–	X	X	X
Fuel production	X	X	X	X	–	–	–	O	–	–	O
Refining	–	–	X	–	–	–	–	X	–	–	–

Figure 14. Job categories and fuel types.

Job category	AR6 Scenario Variable	ModAct	GS	Neg	Ren	LD	SP

Construction & Installation	Capacity Additions | Electricity	-	-	3	-	3	-
Manufacturing	Capacity Additions | Electricity	-	-	3	-	3	-
O&M	Capacity | Electricity	-	-	-	-	2	-
Fuel Production	Resource | Extraction	1	1	1	-	-	-
Refining	Secondary Energy | Liquids	-	-	-	-	-	-

Table 3. Variables in AR6 Scenarios used for each job category and data availability.

Workaround 1: Extraction / Fuel production

The data for the green boxes can be recovered easily by the addition (subtraction) of the Trade variables to (from) the Primary Energy variables. These are reported in all of the scenarios in question and thus pose no further difficulties.

Workaround 2: Capacity / Operation & Maintenance

The purple box indicates that for the LED scenario, the Capacity values are missing. In this regard, we draw on the original LED study that contained variables for Capacity and Secondary Energy per Technology. Dividing Capacity by Secondary Energy yields a productivity factor that - after splitting it up into the R5 regions - we can multiply with the Secondary Energy values reported in the AR6 LED scenario to finally obtain the Capacity values split up by region. Importantly, this method provides the first capacity value for the LED scenario in the year 2020. As we will show in the next workaround, in order to calculate capacity additions in 2020, we need a capacity figure for a time period that precedes that year. Thus, we carry the 2010 value of Capacity over from the ADVANCE_Reference Scenario of the MESSAGE-GLOBIOM 1.0 Model, which is closely related to the MESSAGEix-GLOBIOM 1.0 Model from which the LD IMP stems from and given the 2010 value is fixed and observed, we deem this procedure to be legitimate.

Workaround 3: Capacity Additions / Construction & Manufacturing

The blue boxes indicate that for the Neg and LED scenarios, also the Capacity Addition values are missing. These are used for both the calculation of Construction and Manufacturing jobs, so recovering Capacity Additions will recover both these categories at once.

a. Investments and Capital Costs

The first possibility in this regard is to use Investment (in billion US$/year) in conjunction with Capital Cost (in US$/KW). By transforming the units and then dividing Investments by Capital Costs, one would end up with a measure of GW/year which is exactly how Capacity Additions are reported. This procedure failed due to lack of data. Investment is only available for six of the ten technologies in the LED scenario. Capital Cost was not available at all for LED. We tried to recover the Capital Cost for LED through other MESSAGE scenarios which might be comparable, but Capital Cost was only available there for six technologies which were not necessarily the same as the Investments. We ended up having both Investments and Capital Costs for only two technologies. A tentative calculation showed high correlation between these calculated Capacity Additions and the truly reported ones, but as outlined above it was not possible to recover it for all technologies. On top of that, for the Neg scenario, not

even Investments are available which could also not be recovered from other scenarios. Therefore, this approach was abandoned.

b. Difference between Capacity

The other option is to take the difference between reported Capacities in adjacent time periods and make some retirement adjustments. This is needed because the difference between these capacities represents a lower bound to the actual Capacity Additions and might miss some of the true added capacity in some cases. If for example, the capacity for Solar PV rises in the years 2070 to 2080 from 800GW to 900GW, the difference is 100GW. The True Capacity Additions however that are relevant for Construction and Manufacturing jobs might be 500GW, because 400GW (from the original 800GW) were retired in t (2070), and then 500GW were added to result at 900GW in t+1 (2080) Total Capacity. The retirement rate in this example is 50% (400GW/800GW) in time t (2070). True Capacity Additions in this simple example can thus be recovered as:

Capacity Additions,t+1 = Cap,t+1 - (1 - Retirement Rate,t) * Capacity,t

= 900 - (1 - 0.5) * 800 = 900 - 400 = 500 (in GW/year).

The Capacities for Neg are reported and for LED they have been calculated with Workaround 2 from above. With regards to the retirement rates, we start from lifetimes of power plants as reported in the WITCH model (https://doc.witchmodel.org/energy-supply.html), from which we can compute exponential depreciation rates for each technology. This is a more conservative approach assuming steady retirement rates for different technologies. Another option to recover retirement rates is by taking the average retirement observed in the other scenarios. Both Capacity and Capacity Additions are available in seven of the nine IMP scenarios. For these, I have calculated the effective retirement rates per technology, region and year according to the example above. You can see the result of this in retire_model.png. The rationale behind this is the following: Different regions are at different development levels and thus retire power plants at different stages. With regards to technologies, some - for example fossil fuels - might retire a lot more in the near term, whereas solar and wind which are being constructed right now will be retired (and rebuilt, leading to high Capacity Additions) in big chunks in the far future (2070 onwards). This also legitimizes the calculation of specific retirement rates for different years. From this we can take the average of the retirement rates across models and then a rolling mean. Here one can effectively see what I described before: Retirement rates differ across technologies, but also regions and time. For example, as hinted at, for Wind and Solar the retirement rates go up significantly in the mid to long-term, while for fossil fuels they stay rather constant.

With these retirement rates at hand it is simple to go back to the Capacities reported in Neg and LED and with the formula described above calculate the Capacity Additions. Lastly, it is to be noted that Capacities are reported in GW while Capacity Additions are GW/year. Thus, after extracting the time steps in which Capacities are reported in each scenario, the calculated Capacity Additions are divided by those time steps to arrive at a value in GW/year.

Aggregated Wind Reporting in REMIND Scenarios

To complete the data recovery process, we need to deal with a particularity in reporting pertaining to the REMIND Models which provide the *Ren* and *SP* IMPs, for which Wind variables are not split up into Onshore and Offshore but reported as one aggregated figure. We assume conservatively that all Wind Capacity will be Onshore in this cases and adjust the numbers accordingly.

Redistribution, Technical Progress and Convergence

At this point we have recovered the variables for the IMP scenarios as needed for the employment calculations. A few more adjustments to the data are now made to reflect observed changes in employment worldwide. For one, we are redistributing the energy quantities for Manufacturing of Solar PV according to a key which reflects current

manufacturing shares. If it were not for this redistribution, we would assume that the Solar PV panels are manufactured in the country in which the capacity is added, likely overestimating the jobs needed in parts of the world which are investing in solar but importing the manufactured panels from e.g. China, and underestimating jobs created in countries such as China which are exporters of solar PV technology. The effects of this redistribution for Solar PV on job counts can be seen in Figure 15.

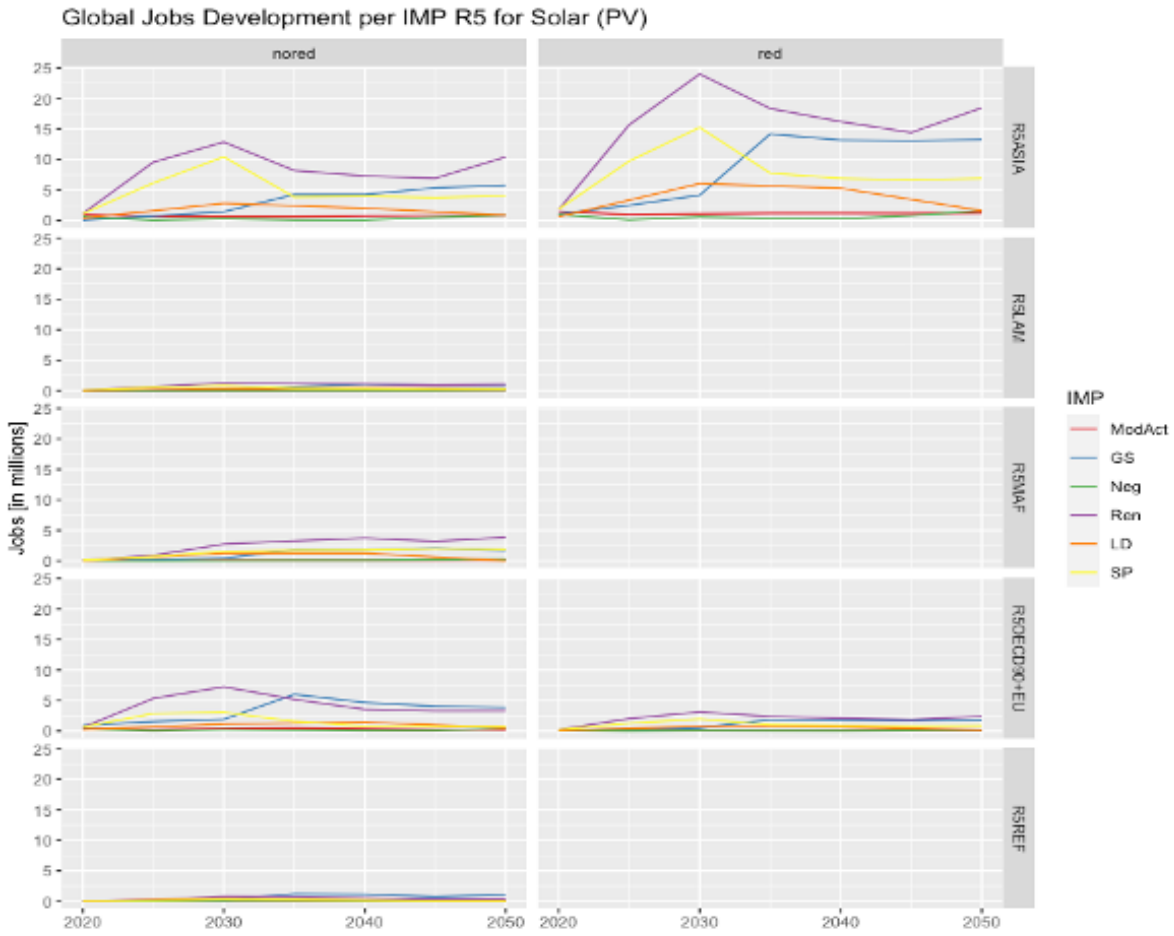

Figure 15. Global Jobs Development per IMP R5 for Solar (PV).

Next, we apply a twofold decrease in job intensities. First, we assume technical progress that reduces energy jobs intensity annually by 0.75% (van der Zwaan et al., 2013) for renewables and 0 for other technologies. This is justified as the newer technologies for renewable fuel production offer margins for improvement of processes, whereas fossil fuel production might be at limits of efficiency. This progress is applied until 2050 and remains flat from then on. Second, we assume a convergence of job intensities across R5 regions for each job category and fuel type to the most efficient production process in 2050. For each job category and fuel type, the lowest job intensity in 2050 across all R5 regions is identified, and all other regions converge exponentially to this value and remain flat thereafter. How this technical progress and convergence compares to the baseline case without these adjustments is shown in Figure 16.

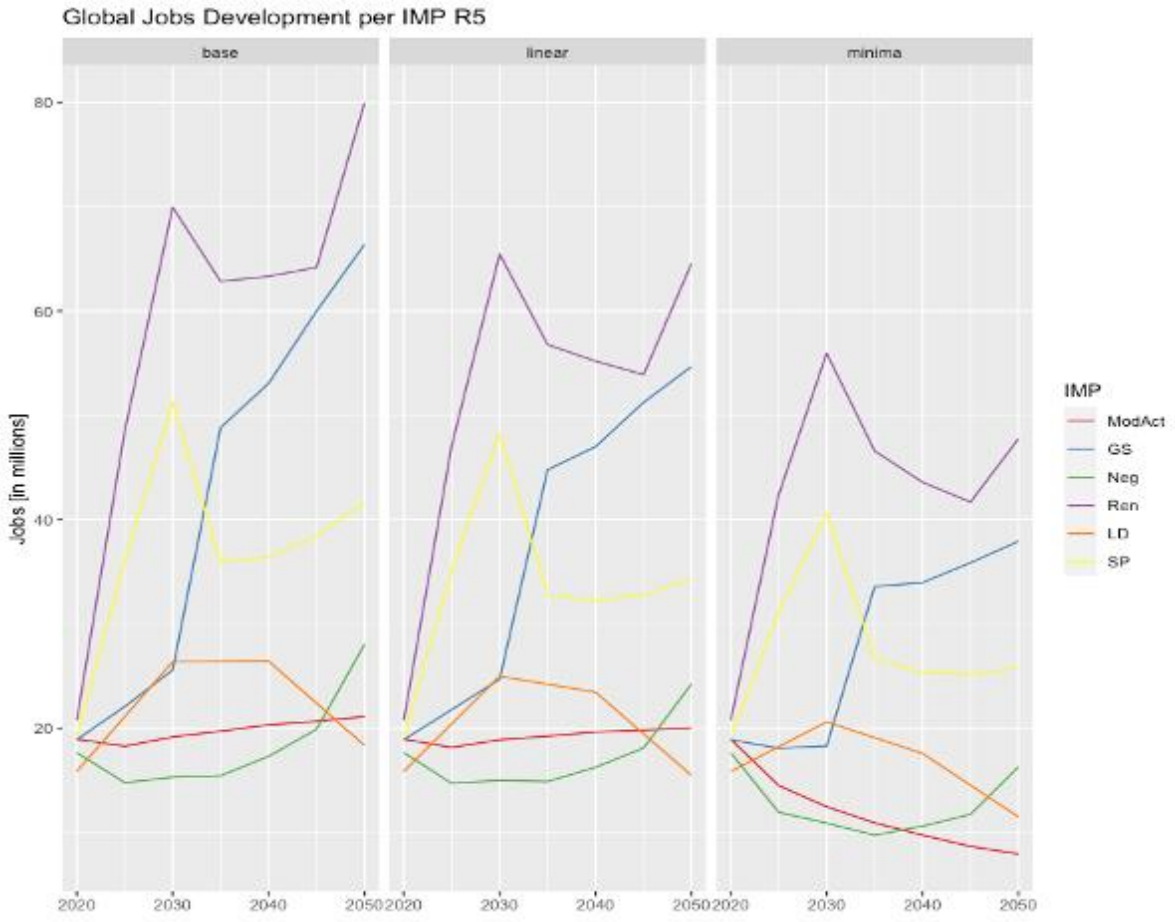

Figure 16. Effect of Technical Progress and Convergence on Global Jobs Development per IMP R5.

Base Line 2020 and Standardization to Total Primary Energy

With these adjustments carried out, we can finally calculate the employment values by simply multiplying the respective energy quantity with each job intensity in the respective region and at each time point. Afterwards, the employment numbers of the 2020 base year are subtracted from all other years to display the results in terms of added jobs with respect to today. Lastly, these job counts are then standardized to Total Primary Energy reported in the scenarios to obtain a more comparable figure across different models.

3.4.4.2 Results

Figure 17 shows total employment numbers with respect to 2020 values for the six IMPs. We can see large differences between scenarios. *Ren* and *SP* have large increases in the short run, and while *Ren* stays at a high level, *SP* drops down and *GS* catches up fast. This behavior can be explained by looking at Figure 18. What drives the creation in the short term clearly are the Construction and Manufacturing jobs in these scenarios, with O&M taking over once the capacity has been installed and needs to be maintained from then on. Extraction drops for all but the *ModAct* scenario. Figure 19 then dives into the different fuel types and uncovers that expansion in Solar PV is largely responsible for the Construction and Manufacturing job creation, whereas Coal is phased out. Figure 20

displays this information in a slightly different way, but the narrative remains unchanged. Finally, the map in Figure 21 shows that most of the jobs across scenarios are created in Asia, which is again due to the high share of Solar PV Manufacturing that has been redistributed to this region above (cf. Figure 15). All in all, It is not necessarily the fiercest mitigation pathways that come out with the highest employment numbers. *LD* for example in the long run comes out with fewer jobs than more conservative scenarios as one of its core objectives is to reduce demand and lower energy use to begin with, thus creating less jobs in the energy sector. It is important to highlight that the jobs displayed here are exclusively supply side jobs however, and thus a potential catching up of some of the scenarios through demand side jobs is not captured by this analysis.

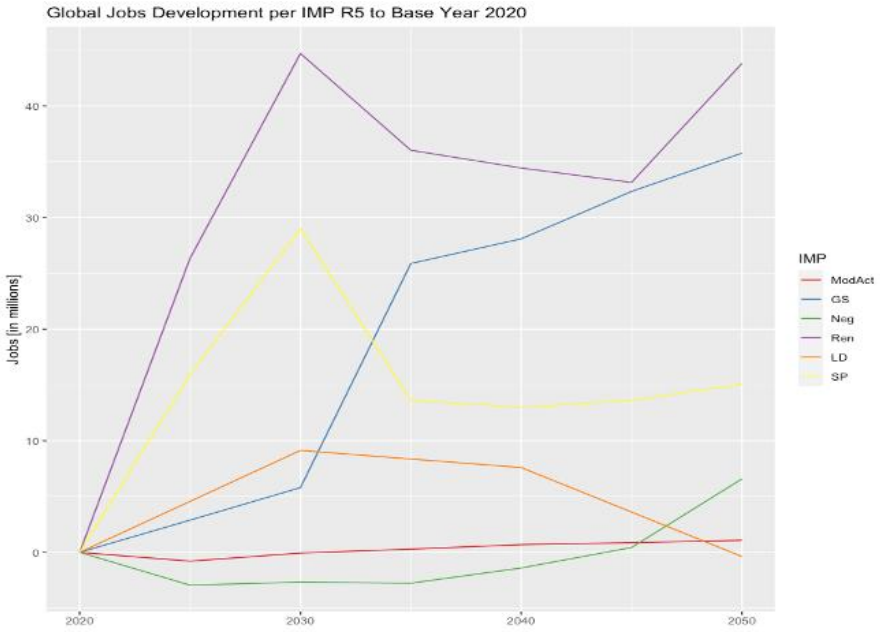

Figure 17. Global Jobs Development per IMP R5 to Base Year 2020.

Figure 18. Global Jobs Development per IMP R5 and Category to Base Year 2020.

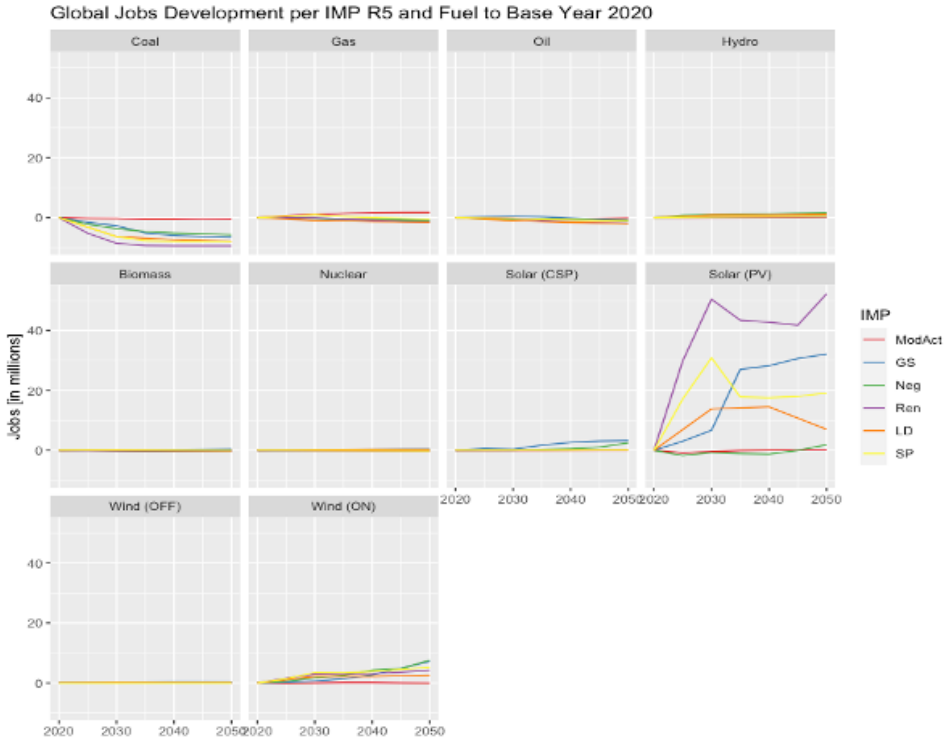

Figure 19. Global Jobs Development per IMP R5 and Fuel to Base Year 2020.

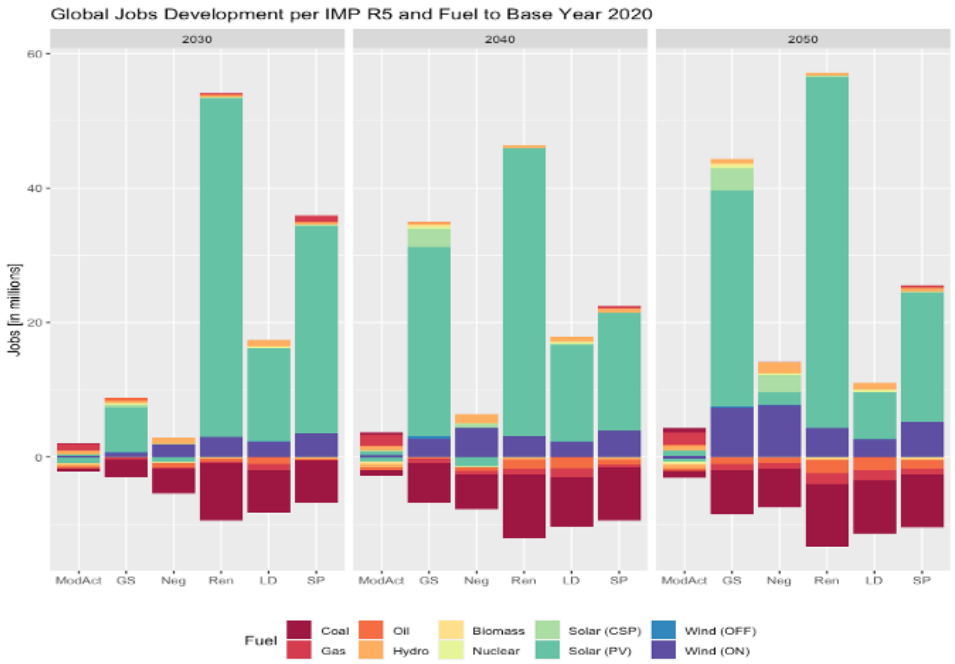

Figure 20. Global Jobs Development per IMP R5 and Fuel to Base Year 2020.

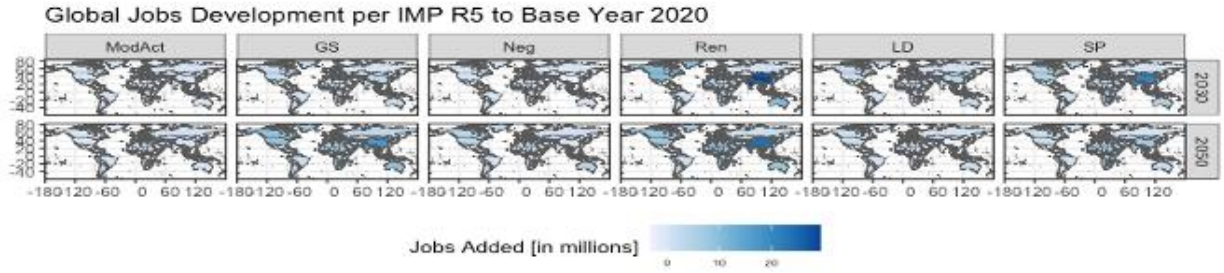

Figure 21. Global Jobs Development per IMP R5 to Base Year 2020.

4. Discussion

In this report, we introduce a framework that enables a multidimensional comparison and evaluation of scenarios from a wellbeing perspective. We position our framework in the broader discussion of the wellbeing concept and the current academic discourse about its role in climate mitigation.

To assess the usefulness of our framework, we compare a few illustrative scenarios using key proposed indicators. While this analysis is purely illustrative, we gain several significant insights. 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, we observe 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.

Future research should explore which consumption patterns are plausible and acceptable to the general public, who are assumed to change their lifestyles. Therefore, it is crucial to incorporate a more comprehensive set of indicators and scenarios to provide policymakers with more accurate information to make informed decisions that align with both climate mitigation and societal wellbeing goals.

Modelling Low Energy Demand Futures for Transport: Current State and Research Needs

Hugh Thomas, Luis M. Martinez, Paul Natsuo Kishimoto,
Felix Creutzig, Yamina Saheb

February 27, 2024

Abstract

Rising global greenhouse gas emissions in the transport sector pose a major challenge to reaching Paris Agreement targets. This raises the question of how technology, infrastructure, societal trends and policies can influence transport demand and thus also emissions, energy demand and service levels. Here we review the literature on factors relevant to shifting total transport activity and mode shares, categorised into megatrends, socio-behavioural, infrastructural and technological aspects. For each factor, we summarise current approaches used to model and measure the impact of each factor on transport systems. As a result, we propose a taxonomy to help the classification of current transport demand modelling approaches. We comment on the suitability and sufficiency of existing modelling approaches for representing (transport) scenarios consistent with the targets of the Paris agreement in models of the entire global energy system. We conclude that factors affecting transport demand are insufficiently represented in current global integrated assessment modelling approaches and pathways that indicate potential emissions reductions. Improving the comprehension and representation of diverse factors that affect transport demand holds promise for generating well informed policy recommendations. Consequently this can influence the factors and their role in mitigating climate change in pathways compatible with the targets of the Paris agreement.

Keywords: Transport demand modelling, Climate change mitigation, Transport demand, Energy demand transformation, Megatrends, IPC

Global trajectory for urban passenger transport decarbonisation: a policy-based modelling approach

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Abstract
This paper estimates the evolution of urban passenger travel volumes and related pollutant emissions in the 9,234 urban areas in the world. It builds on a hybrid four-step model and systems dynamic modelling approach considering socio-economic projections, estimations of urban growth, transport supply provision and policy assumptions to provide results for 19 world regions. Thanks to its detailed representation of 18 transport modes and 20 policy measures, the model enables identifying the critical leverage for achieving sustainable transport systems and promoting efficient transport policies. A *High Ambition* policy scenario combining the requirement of a high well-being with low energy and material resource consumption pathway with improved technology developments is put forward aiming at reaching the global commitments of the Paris Agreement.

Keywords: Urban passenger transport · Urban mobility · Transport modelling · Sustainable mobility · Policy quantification · Decarbonisation trajectories

Modelling intercity and long-distance passenger travel decarbonisation pathways

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Abstract
This study addresses the imperative to decarbonise intercity and long-distance travel in alignment with the Paris Agreement, a transport sector which is often overlooked. Focusing on global intercity transport, the paper assesses the impacts on travel demand and related CO2 emissions of two potential future scenarios relying on a global multimodal model that represents 5 different transport modes (air, rail, car, bus, motorcycle). Projections indicate demand will increase towards 2050 under both scenarios, with the *High Ambition* scenario showing a reduction of 13% of travel activity growth compared to the *Current Ambition*. To decouple travel demand growth from emissions, it becomes imperative to accelerate adoption of clean fuels and fleets. The paper discusses scope and challenges of different decarbonisation policies to promote shifts to less-polluting modes and to reduce the carbon intensity of each transport mode. Finally, the paper highlights that intercity and long-distance travel contributes 24% of the global passenger transport CO2 emissions; however, these being driven by a minority of the world's population. This underscores the socio-economic disparities inherent to long-distance travel behaviour, with individuals in affluent regions exhibiting higher travel propensity.

Keywords: long-distance travel · decarbonisation · scenario modelling · decarbonising aviation

Modelling global freight decarbonisation pathways

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ABSTRACT
This paper addresses the urgent need to decarbonise the global freight sector. Using the ITF PASTA modelling framework,
it projects freight activity and emissions to 2050 under two policy scenarios of differing climate ambitions. Results reveal
that without significant efforts and higher ambitions, global freight transport will not meet climate goals. Regional analyses
underscore the importance of international cooperation. The study also discusses challenges in achieving efficiency gains and
modal shifts and emphasises the vital role of demand management in successful decarbonisation efforts.

Keywords: Freight decarbonisation, Hard-to-abate, policy scenarios, Demand management

Rethinking Transport Sustainability: Insights from the ITF PASTA Global Fleet Model

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Abstract

This paper addresses the global challenge of aligning the transport sector with the Paris Agreement, emphasising the strong interaction between transport demand and vehicle fleet dynamics. The integration of the ITF Fleet model with the ITF PASTA framework provides a unique ability within the Transport Global Energy models. Two scenarios, Current Ambition and High Ambition, reveal how the role of vehicle electrification and low-carbon freight technologies is crucial, with a focus on regional variations. Analysis of second-hand vehicle flows underscores challenges in emerging economies. Effective governance and harmonised regulations are deemed essential for a fair and sustainable global transition to clean transport technologies, emphasising the need for accelerated actions beyond current policy levels.

Keywords: vehicle fleet, scrappage, used vehicles, global model

Shared mobility's role in sustainable mobility: past, present, and future

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Keywords: shared mobility, taxonomy, urban transportation, technological disruption, emerging services, sustainability

ABSTRACT

This paper reviews shared mobility, a prominent urban transportation concept with considerable 12 potential to contribute to more sustainable urban mobility. Shared passenger mobility spans diverse 13 services, often leveraging technological advances and disruptions like smartphones and data analytics to 14 optimise transport resources. Given the broad range of services, a shared mobility taxonomy is 15 proposed, accommodating evolving services. Key challenges for delivering efficient and effective shared 16 mobility services with lower environmental impacts are also identified. Finally, the ITF transport demand 17 models are used to analyse policy implications and potential effects quantitatively. It presents a possible 18 scenario for the global evolution of these services to 2050. Results emphasise the sector's role in 19 transport decarbonisation in the present and future. They show that shared mobility may reduce 20 resource use and mobility externalities (i.e., CO2, local pollutants, congestion, urban space use) but that 21 the uptake will differ between the Global South and Global North cities.

Summary of activities within EDITS network

The project has received funding from the Research Institute of Innovative Technology for the Earth (RITE) under subcontract agreement D06710.

Introduction

This report summarizes a contribution of the ITF to the Energy Demand changes Induced by Technological and Social innovations (EDITS) research community. The aim is to provide an analysis how demand disruptions in the transport sector have been incorporated in the ITF modelling framework. This introduction aims at help on the assessment and creation of a common framework of communication with the global energy models as IIASA MESSAGE model.

The reports describes the ongoing activities of ITF within the Transport Working Group but also the linkages with the other Working Groups.

Background

EDITS carries out research to assure the transfer of methodological and modelling innovations across demand-side models, and builds an interactive research and policy network. The project identifies gaps and potentials to enhance novel service delivery models or policy interventions on climate mitigation and the SDGs.

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

The main objectives of EDITS are:

- to create a research community focusing on end-use, demand-side perspectives that further dialogue and cross-fertilisation of research and policy analysis by sharing novel data, novel concepts, methodologies and policy analyses.
- to improve the state-of-art of demand modelling in environmental and climate policy analysis via methods and model intercomparisons and assist the transfer of conceptual and methodological improvements across disciplines, sectors, and environmental domains.
- to better inform policy via structured model experiments and simulations that assess potential impacts, barriers, as well as synergies and trade-offs to other SDG objectives of demand-side policy interventions, particularly in novel fields and service provision models such as digitalisation, sharing economy, or the integration of SDG and climate objectives in synergistic policy designs.

EDITS focuses on both the human and the technical resources by launching an expert network and a demand-side model comparison exercise.

ITF provides expertise contributing in the transport sector by providing state of the art and practise tools and insights of the role of innovations and policies on controlling or reducing transport activity, the derived energy consumption and CO2 emissions.

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ITF activities 2023

Participation in workshops or other EDITS meetings

ITF participated in the workshops presenting the advances in the working group:

- Participation and contribution to the EDITS annual meeting (7 November – 10 November 2023)
- Presentation of the advancement of the transport working group.
- Discussion of the finalisation of the Transport review paper.
- Participation and contribution to the EDITS quarterly meetings (4 – 5 April 2023, 12-13 June 2023,26-27 September 2023). Presentation of the advancement of the transport working group.

Joined EDITS Working Groups research

Data group: Participation in the methodology paper on data sharing among models. Setting up the standard description of model data inputs and outputs to make model components more understandable and highlight potential model connections or gaps.
Narratives group: Participation in meetings and provide feedback about the approach in the transport sector and the connection with the other sectors.
Industry group: Participation as a listener in the meetings to be aware of the approach and linkages to freight demand adaptations.
Buildings group: Participation as a listener in the meetings to be aware of the approach and linkages to land-use implications on urban transport.
Protocol group: Participation as a listener in the meetings to be aware of the approach and linkages to transport working group.
Well-being: Active member and participant in the events and contributes to the standard datasets.
Member of Data and Cost Fast Track paper.

Transport Working Group research

The members of the working group are currently developing a review paper on the demand transformative phenomena in the transport sector. The paper is being developed in a shared file (Overleaf: https://www.overleaf.com/project/61b891b6ca0d05531f5cb762). The paper has a temporary title: "Novel transport technology trends and implications for modelling: a review". The complete draft is expected at the end of March 2024. The paper is ready to submit after internal review from EDITS members.

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ITF-specific research to feed into EDITS

ITF developed in 2023 a set of work dedicated to EDITS to improve the model to represent demand-related transformational measures and implement the LED narrative in the scenario 'High with Low'. We developed for documentation four papers to be submitted to the Nature Sustainable Mobility and Transport devoted to the modelling of urban and non-urban passenger and freight activity, respectively and the fleet model. The papers describe the ITF modelling framework of transport demand and fleet models, how the narrative of the 'High with Low' narrative has been implemented and tested, and the results. Additionally, a devoted Shared mobility review paper was submitted and accepted in Annual Review of Environment and Resources titled " Shared mobility's role in sustainable mobility: past, present and future".

Apart from the reports, a dataset of a detailed assessment of results by vehicle, year and region of transport, energy demand, and derived transport CO_2 emissions.

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EDITS WG4 Wellbeing

Report to RITE

February 2024

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1. Introduction

1.1. Purpose and context of EDITS WG4 Wellbeing

Context: The EDITS (Energy Demand changes Induced by Technological and Social innovations) network (iiasa.ac.at/projects/edits) is a research community that aims to develop new approaches to understand and model reductions in energy demand. The work of EDITS finds its roots in the 2018 Low Energy Demand (LED) scenario, and the 2023 updated "High-with-Low" scenario narrative, a normative explanation on achieving wellbeing for all with low energy and material resource consumption. The focus on wellbeing made a more systematic approach to understanding and operationalizing wellbeing more central, with a continuously operating group and process, as opposed to a thematic meeting or "fast-track" initiative, and led to the creation of the EDITS Working Group Wellbeing (WG4 Wellbeing).

Approach to wellbeing: There are many approaches to defining and understanding wellbeing, which within EDITS we broadly define as a state of thriving, which involves full participation in society, a sense of prosperity and of leading a good life, in which basic needs are satisfied, for current as well as future generations. Hereby we consider both the eudaimonic approach, following Aristotle, reflecting a meaningful life, and hedonic wellbeing, seeking a life of pleasure and free of pain and fear (e.g., Venhoeven et al., 2013; see also the SWICE position paper on wellbeing).

Purpose: With the growing focus on wellbeing across EDITS, and the need to systematically explore and model demand-side approaches satisfying both low resource use and high wellbeing, the EDITS Working Group Wellbeing (WG4 Wellbeing) was created in the spring of 2023, with the general aim to understand how low carbon lifestyles affect wellbeing. Based on ideas expressed in the EDITS Quarterly (05.04.2023), around 20 members of EDITS interested in wellbeing met on Thu 04.05.2023, effectively starting WG4 Wellbeing and defining its main goals for the year 2023:

1. Support the integration of wellbeing in EDITS goals, models, narratives, and communication
2. Contribute to understanding of how reductions in energy demand affect wellbeing

Additionally, we aim to help include wellbeing in societal dialogue, political debate, and policy.

1.2. WG4 Wellbeing process, timeline, activities

1.2.1. Topics of WG4 Wellbeing

To best reach the goals stated above, WG4 Wellbeing aims to cover the following topics:

A. Inventory of definitions and indicators of wellbeing
    - We will differentiate between micro and macro level indicators, and objective versus subjective indicators of wellbeing
B. How to include wellbeing in sectoral models and IAMs?

- Do we need different approaches for different models? Which conceptualization of wellbeing would be most suitable (macro vs micro, subjective vs objective)? How to link to DLS?

C. Evaluate effects of low demand scenarios on wellbeing and acceptance
   - We focus on individuals' subjective evaluation of low demand scenarios.
   - Identify relevant data sets in different countries and analyze the data.

1.2.2. Activities of WG4 Wellbeing

In the last year, WG4 Wellbeing conducted the following activities:

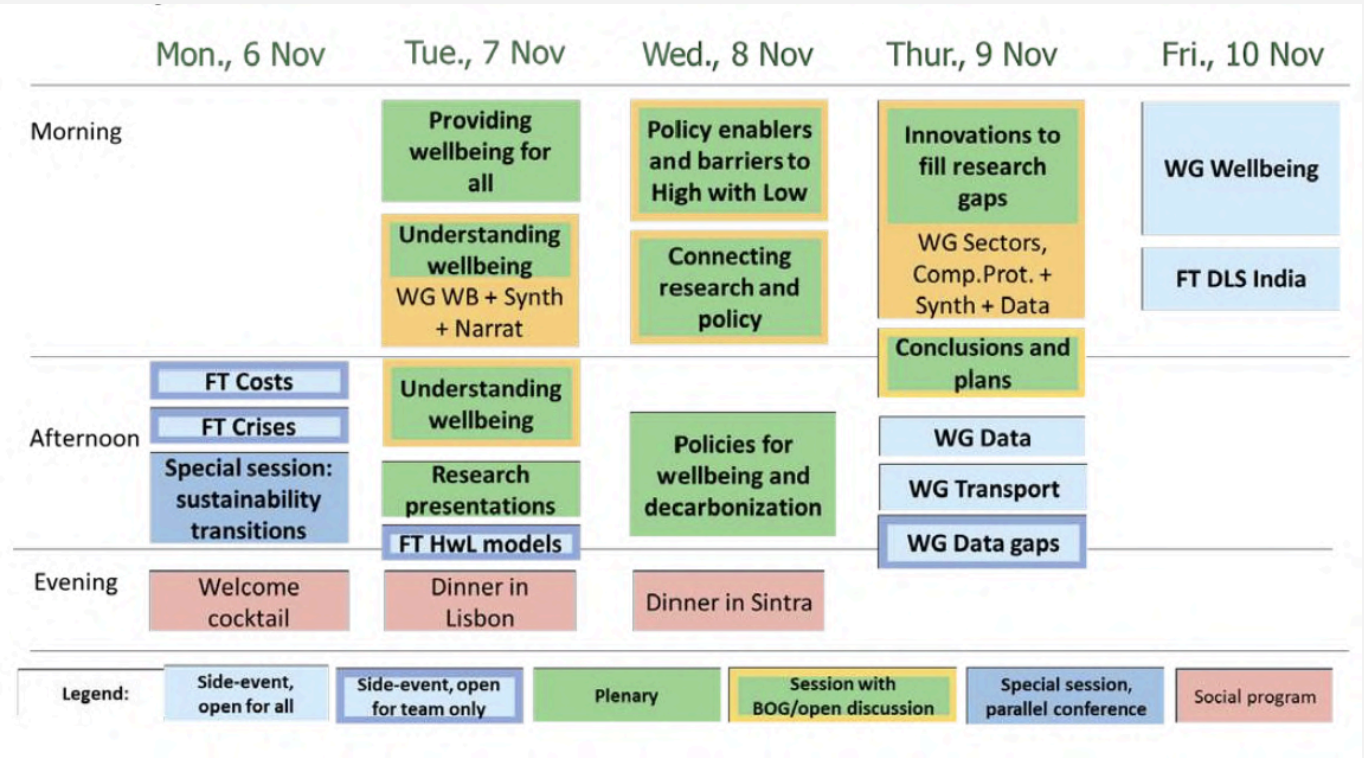
1. Dedicated WG4 Wellbeing meetings, approximately every two months, typically involving around 20 of current 35 members
2. Breakout sessions and plenary presentations in every EDITS Quarterly Meeting
3. Plenary and dedicated sessions in EDITS Annual Meetings (in-person)
4. Thematic meetings of a smaller subset of WG4 Wellbeing members on a specific topic, such as wellbeing indicators
5. Management meetings involving WG4 Wellbeing co-leads and a small number of other participants
6. EDITS Fast-track proposals submitted with a wellbeing component, supported by WG4 Wellbeing. Of these, the following are successful: FT1 "WELL-with-LOW - Wellbeing Metrics and Assessment of LED-type Policy Options", FT3 "Patterns of Diffusion in Social Innovations", and FT8 "Decoding decent mobility: Relating needs, infrastructure, and energy use explicitly". These will be realized in 2024-25 financial year.
7. Independent work related to wellbeing by EDITS members (details in Chapter 5)

All meetings to date were online, except the in-person sessions in EDITS Annual Meetings.

1.2.3. Wellbeing at the EDITS Annual Meeting 2023

As a example of how wellbeing is integrated in EDITS and how WG4 Wellbeing contributes, let's review the EDITS Annual Meeting, which took place in Lisbon 06-10.11.2023 (for a detailed summary, please read the IIASA report on the Annual Conference):

A. Different sessions focused on wellbeing (titles of sessions):
   a. Providing wellbeing for all (plenary)
   b. Understanding wellbeing (plenary)
   c. Policies for wellbeing and decarbonization (plenary)
   d. WG Wellbeing special session (mainly members, open to all EDITS)



B. A number of contributions covering a wide range of wellbeing-related topics was covered in the Annual Meeting (Titles followed by short summaries below):
    a. Sascha Nick: the SWICE wellbeing+sufficiency project
    b. Anne van Valkengoed: impact of low-carbon scenarios on perceived quality of life (addressing one of the three main research questions of WG4 Wellbeing)
    c. Sascha Nick and Elina Brutschin: sustainable wellbeing, universal needs, context-specific satisfiers, and societal influences on wealth
    d. Summary and way forward, moderated by Benigna Boza-Kiss

Summary of interventions

Sascha Nick, Laboratory of Environmental and Urban Economics (EPFL), Switzerland presented the SWICE project, proposing a systems approach to sufficiency, wellbeing, and transition in the Swiss habitat. In Swiss buildings, energy use has reduced by 33% in the past 31 years, and emissions per square meter have decreased by 2/3. However, square meters have increased by 50%. To address these challenges, action levels and high-leverage points, including mindset shifts, are necessary for system solutions. For a more detailed report, see Section 4.

Anne van Valkengoed, University of Groningen, the Netherlands examined the impact of low-carbon lifestyle scenarios on perceived quality of life. She presented results of a study among Dutch participants that evaluated a low carbon lifestyle scenario developed by the Dutch youth climate movement, depicting a low carbon lifestyle in the Netherlands in 2040. For a more detailed report on the results of the study, see Section 3.

Sascha Nick, Laboratory of Environmental and Urban Economics (EPFL), Switzerland and **Elina Brutschin**, International Institute for Applied Systems Analysis (IIASA), Austria described sustainable wellbeing within planetary boundaries, presenting various preceding concepts that explore universal needs, context-specific satisfiers, and societal influences on wealth, these include: Doyal & Gough

(1991), Max-Neef's matrix of needs and satisfiers, Di Giulio & Defila (2020), Lamb & Steinberger (2017) and O'Neill et al (2018) "LiLi".

They proposed the following all-encompassing definitions:

1. Wellbeing is the result of satisfying basic needs in all major human needs approaches.
2. Basic needs are universal, constant over time and cultures, classifiable, non-substitutable, and satiable.
3. Satisfiers, separate from needs, are culturally specific but have common characteristics. Resource need strongly depends on the dominant satisfiers.
4. Desires, potentially infinite, often disconnected from needs, are not useful in planning for wellbeing.
5. Multidimensional needs satisfaction is a necessary condition for and strongly correlates with wellbeing (O'Neill et al 2018, Helliwell 2008).
6. Decent Living Standards (DLS) approach shows that all material prerequisites for wellbeing can be satisfied with 10% of final energy used in rich countries today, while providing wellbeing for all.
7. Significant gaps in providing shelter, nutrition, health, mobility, and socialization remain in all world regions. Closing all DLS material provisioning gaps requires new infrastructure which could be built with a one-time investment of 290 EJ, or 9 months of world's final energy use (Kikstra et al 2021).
8. Provisioning factors strongly affect the effectiveness of satisfier provision: positively (public service, public health, clean energy access, democracy, equality) or negatively (extractivism, economic growth) (Vogel et al 2021)

Building on suggestions made by others, there's a call for a more systematic approach that bridges sectoral and global aspects. It aims to expand the context-specific view of need satisfiers and promote a more holistic approach to need satisfaction.

1.2.4. WG4 Wellbeing participants

	Name	Organization	Topics of interest	Level of foreseen engagement
1	Linda Steg	U Groningen		co-lead
2	Sascha Nick	EPFL	Wellbeing and sufficiency, societal organization, satisfiers,	co-lead
3	Alessio Mastrucci	IIASA	link to WG1-Buildings, fast-track on living standards in India in	research, paper writing, link to modelling
4	Alice Garvey	U Leeds		
5	Aljoša Slameršak	Universitat Autònoma de Barcelona		
6	Anne van Valkengoed	U Groningen		
7	Arnulf Grubler	IIASA		
8	Benigna Boza-Kiss	IIASA	energy demand reductions by technological innovations and social	discussions (meetings), policy relevance, maybe paper writing
9	Benjamin Best	WI	Sufficiency policy, energy demand reduction	meetings, indicator development/research, paper writing, revi
10	Caroline Zimm	IIASA	energy & material demand and linkages to subjective wellbeing; habit	research, paper writing, meetings
11	Christian Hauenstein	Albert-Ludwigs-Ur		
12	Dahyun Kang	RITE	energy demand(building) for wellbeing, incorporating wellbeing into m	meetings, research
13	Diana Urge-Vorsatz	CEU	we can help with modeling buildings related sufficiency	research, modeling, paper writing
14	Dominik Wiedenhofer	BOKU	biophysical basis of wellbeing at macro-level & time-use,	meetings, networking, synergies with ongoing research
15	Doris Virág	BOKU		
16	Elena Verdolini	CMCC	Objective wellbeing, subjective wellbeing and the concept of Just	
17	Elina Brutschin	IIASA	DLS and SWB	
18	Frauke Wiese	EUF	wellbeing indicators, evaluating scenarios based on wellbeing	discussions/meetings, research, writing
19	Jan Streeck	BOKU	potential overlap to fast track on stocks-flows-DLS; link to	meetings, evaluation of fast-track overlap
20	Jihoon Min	IIASA	Wellbeing in global south context; linkage to material and energy;	research, paper writing, modeling, empirical(?)
21	Johan Velez	U Freiburg	wellbeing footprints withing income levels and countries	
22	Joyashree Roy	AIT	Wellbeing constituents, determinants and empirical studies	Reserach paper writing, Concept , framing, indicator /metric de
23	Leticia Magalar	CMCC	Links between wellbeing and minimum material consumption	meetings, modelling, writing
24	Luis Martinez	International Transport Forum, OECD		
25	Masahiro Sugiyama	U Tokyo	General approach to combining scenarios and surveys; framing of	
26	Miyuki Nagashima	RITE	link to Protocol WG, measuring of high wellbeing, incorporating	meetings, research
27	Muhammad Huzaifa Butt	AIT	Sustainable transportation modes and wellbeing in urban areas	
28	Oreane Edelenbosch	U Utrecht	link also to the data group - thinking of dls indicators	meetings, modelling, writing
29	Roberto Schaeffer	COPPE/UFRJ	Energy and materials demand for human well-being to incorporate	
30	Shonali Pachauri	IIASA	we have focused on objective measures of wellbeing so far and more	research, paper writing, modeling
31	Shreya Some	AIT	Quantifying wellbeing.	research, paper writing, indicator development, modeling
32	Souran Chatterjee	U Plymouth	.	research, paper writing, modeling
33	Yamina Saheb	Sciences Po/UNIL	Estimates of sufficiency impacts of health improvement	research, paper writing, indicator development, modeling
34	Yiyi Ju	Waseda U	Modeling wellbeing in IAMs / using GCAM + experience with IAM inter-comparison	
35	Yohei Yamaguchi	Osaka University		

The current member list is maintained on the EDITS SharePoint: [WG Wellbeing People](#).

2. Wellbeing Indicators

2.1. Background and need for indicators, focus of WG4 Wellbeing

EDITS aims to explore, describe, model, and operationalize high-wellbeing, low-resource futures. Examples are the 2018 Low Energy Demand (LED) scenario, and the more recent 2023 “High-with-Low” scenario narrative. To understand how low carbon lifestyles and reductions in energy demand affect wellbeing, we need to identify key indicators of wellbeing, starting with a literature review.

2.2. Methodology

First, based on the approach to wellbeing chosen for EDITS, the main categories or wellbeing indicators were identified from the literature on the following topics:

A. Human needs
B. Subjective wellbeing and quality of life
C. Composite indices, representing a weighted average of multiple indicators
D. Satisfiers
E. Local Environment: environmental indicators such as pollution, heat, or noise, which affect human wellbeing (as opposed to ecosystem health)

We identified around 80 wellbeing indicators, in the main categories listed above. This initial list was shared in the EDITS wellbeing community, and numerous suggestions were provided and integrated in the indicator list.Next, the indicators were categorized by type of indicator, notably (micro vs macro, and subjective vs objective, core vs supplementary). This list was again shared with the EDITS wellbeing community, and additional adjustments made.

2.3. Current results and next steps

A comprehensive and consistent list of 116 wellbeing indicators was developed (see pp. 8-9).

The full list can be accessed and downloaded from go.epfl.ch/WI.

Next steps:

- Engage EDITS modelers; if and as needed, adjust indicators to be useful to modelers
- Fast-track “Wellbeing with LED-type policy” to develop policy analysis tools integrating energy security, climate as well as wellbeing indicators for a multi-dimensional analysis. The focus would be on national level, short, to medium-term analysis (to 2030) of concrete prototypic policies instead of the usual long-term scenarios. This planned but not yet validated (as of 15.02.2024) fast-track proposal involves several members of WG4 Wellbeing.

Wellbeing Indicators

DRAFT updated 15.02.2024

Please send comments and suggestions to sascha.nick@epfl.ch

#	Category	Indicator	Objective-Subjective	Macro-Micro	Core / –	Inequality *	SWICE	What is measured	Suggested formulation	Unit
1	Human Needs	**Health**	O	Ma	core			Physical health: life expectancy at birth, QALY, ...		multiple, depending on option,
2	Human Needs	[Option 1] Subjective evaluation of health	S	Mi	core		Y	Cantril scale, survey	How do you rate your overall health? (0=wo	0-10, dimensionless
3	Human Needs	[Option 2] EQ-5D-5L	S	Mi	core		Y	Self evaluation of mobility, self-care, usual activities, pain / disc	See EQ-5D-5L; do not modify questions.	Health state (one of 3125 discr
4	Human Needs	[Option 3] QALY	O	Ma	–			Equivalent life years in perfect health		years
5	Human Needs	**Autonomy**	O-S	M-M	core			Mental health, understanding, opportunity		multiple, depending on option,
6	Human Needs	[Option 1] Time autonomy	S	Mi	core		Y	Subjective evaluation of one's ability to organize time and prio	How do you rate your ability to organize you	0-10, dimensionless
7	Human Needs	[Option 2] Control over one's life	S	Mi	core		Y	Subjective evaluation of one's ability to make important life de	How do you rate your ability to make import	0-10, dimensionless
8	Human Needs	**Participation**	O-S	M-M	core			Meaningful particpation in society without impairment		multiple, depending on option,
9	Human Needs	[Option 1] Participation in community activities	S	Mi	core		Y	Subjective evaluation of one's overall particpation in communi	How do you rate your overall participation in	0-10, dimensionless
10	Human Needs	[Option 2] Participation in community decisions	S	Mi	core		Y	Subjective evaluation of one's overall involvement in your com	How do you rate your overall involvement in	0-10, dimensionless
11	Human Needs	[Option 3] Critical partcipation	S	Mi	–			Subjective evaluation of one's ability to meaningfully contribut	How do you rate your ability to meaningfully	0-10, dimensionless
12	Human Needs	Subsistence	O-S	Mi	–					% people
13	Human Needs	Protection / Security	O-S	Mi	–					% people
14	Human Needs	Affection	O-S	Mi	–					% people
15	Human Needs	Understanding	O-S	Mi	–			**Subjective**: subjective evaluation of (a) personal ability to satis	Measuring satisfaction of needs, following M	% people
16	Human Needs	Participation	O-S	Mi	–				- Do you feel our society makes it easy for y	% people
17	Human Needs	Idleness / Leisure	O-S	Mi	–			**Objective**: access to material prerequisites for decent living (D	- Do you feel our society makes it easy for y - Do you feel our society makes it easy for y	% people
18	Human Needs	Creation	O-S	Mi	–					% people
19	Human Needs	Identity / Meaning	O-S	Mi	–					% people
20	Human Needs	Freedom	O-S	Mi	–					% people
21	Human Needs	Perception of deprivation	O-S	Mi	–			People feeling deprived w. respect to at least one need		% people
22	Subjective Wellbeing	**Life Satisfaction**	S	M-M	core		Y	Subjecite evaluation of life satisfaction	Please imagine a ladder, with steps numbere	Cantrill scale 0-10
23	Subjective Wellbeing	Satisfaction with Life Scale	S	Mi	–			Five question about living conditions		5-35, dimensionless (each que
24	Composite	HDI	O	Ma	–			Life expectancy, years schooling, GNI (PPP)		0-1, dimensionless
25	Composite	IHDI (inequality-adjusted HDI)	O	Ma	–			HDI of average person (Atkinson index)		0-1, dimensionless
26	Composite	Years of Good Life (YoGL)	O	Ma	–			Life years, weighted by objective (health / activity limitations, n		Years
27	Composite	Multidimensional Poverty Index (MPI)	O	Ma	–			Weighted deprivation in three dimensions of poverty (Health, E		0-1, dimensionless
28	Composite	OECD Better Life Index	O	Ma	–			Housing, income, jobs, safety, health... (total 11)		0-10, dimensionless
29	Composite	OECD - housing	O	Ma	–			Facilities, rooms/cap, expenditure		0-10, dimensionless
30	Composite	OECD - income	O	Ma	–			Household wealth and income		0-10, dimensionless
31	Composite	OECD - jobs	O	Ma	–			Earnings in job / out of job, unemployment		0-10, dimensionless
32	Composite	OECD - community	S	Ma	–			Quality of support network		0-10, dimensionless
33	Composite	OECD - education	O	Ma	–			Expected schooling, PISA scores, % w. high-school		0-10, dimensionless
34	Composite	OECD - environment	O	Ma	–			PM2.5, satisfaction w. water quality		0-10, dimensionless
35	Composite	OECD - civic engagement	O	Ma	–			% voting, stakeholder in lawmaking		0-10, dimensionless
36	Composite	OECD - health	S	Ma	–			Self-reported health, life expectancy		0-10, dimensionless
37	Composite	OECD - life satisfaction	S	Ma	–			same as WHR		0-10, dimensionless
38	Composite	OECD - safety	O	Ma	–			Homicide rate, feeling safe walking at night		0-10, dimensionless
39	Composite	OECD - work-life balance	O	Ma	–			Hours not working, % working >50h/week		0-10, dimensionless
40	Composite	**SPI**	O	Ma	–			Composite of 57 outcomes on three areas		0-100, dimensionless
41	Composite	SPI - Basic Human Needs	O	Ma	–			Food, water, housing, health care, safety		0-100, dimensionless
42	Composite	SPI - Foundations of Wellbeing	O	Ma	–			Knowledge, healthy environment		0-100, dimensionless
43	Composite	SPI - Opportunity	O	Ma	–			Non-discrimination, advanced education		0-100, dimensionless
44	Satisfiers	Ability of technical systems to satisfy needs	S	Mi	–		Y	Subjective evaluation of infrastructure	How do you feel the physical infrastructure t	0-10, dimensionless
45	Satisfiers	Ability of social systems to satisfy needs	S	Mi	–		Y	Subjective evaluation of public services and social systems	How do you feel the social systems that you	0-10, dimensionless
46	Satisfiers	Food quantity	O	M-M	–			Average food intake per day		kcal per person per day
47	Satisfiers	Food balance	O	M-M	–			Micro+macronutrien balance		% people on EAT-Lancet diet c
48	Satisfiers	Food quality	O	M-M	–			Non-UPF food in diet, kcal (NOVA 1+2+3)		% people
49	Satisfiers	Access to clean water	O	M-M	–			Inside the dwelling or building		0-1, dimensionless
50	Satisfiers	Access to sanitation	O	M-M	–			Inside the dwelling or building		0-1, dimensionless
51	Satisfiers	Housing quantity	O	Mi	–		Y	Access to space, permanent or when needed		m2, rooms, functions per pers
52	Satisfiers	Housing quality	O	Mi	–		Y	Composite indoor air quality, noise, light, thermal-visual-acous		0-1, dimensionless
53	Satisfiers	Thermal comfort - subjective	S	Mi	–		Y	Subjective evaluation of thermal comfort		% people satisfied
54	Satisfiers	Thermal comfort - energy balance	O	Mi	–			Predicted mean vote (PMV)		-3 to 3, dimensionless
55	Satisfiers	Thermal comfort - energy balance	O	Mi	–			Room operative temperature		°C
56	Satisfiers	Thermal comfort - heating and cooling	O	Mi	–			Ability to stay in max 28°C in summer and min 18°C in winter		% people
57	Satisfiers	Sound comfort - subjective	S	M-M	–			Subjective evaluation of sound comfort		
58	Satisfiers	Indoor air quality	S	Mi	–		Y	Percieved indoor air quality		0-10, dimensionless
59	Satisfiers	Quality of light - adequate daylight	S	M-M	–		Y	People experiencing adequate daylight at home		% people
60	Satisfiers	Quality of light - no glare	S	Ma	–			People experiencing no glare self-described as problematic		% people

61	Satisfiers	Quality of light - Melanoptic EDI	O	Mi	–			Melanopic equivalent daylight illuminance		lx	
62	Satisfiers	View quality	S	Mi	–		Y	Subjecite evaluation of view quality		0-10, dimensionless	
63	Satisfiers	View quality	O	Mi	–			Composite of water, vegetation, sky, distant view, diversity, bui		0-10, dimensionless	
64	Satisfiers	Mobility - subjective	S	Mi	–		Y	Subjecite evaluation of ability to move when needed	How do you feel the transport infrastructure	0-10, dimensionless	
65	Satisfiers	Mobility - time and affordability	O	Mi	–		Y	Is the time and cost to reach essential destinations impairing o			
66	Satisfiers	Access to phone, computer, internet	O	Mi	–			Available in household		% people	
67	Satisfiers	Access to primary care	O	M-M	–			Physical proximity, affordability		% people	
68	Satisfiers	Access to hospital	O	M-M	–			Physical proximity, affordability		% people	
69	Satisfiers	Sleep quality and duration	O	Mi	–		Y	Quality-adjusted sleep per night		h per night	
70	Satisfiers	Physical activity frequency and intensity	O	Mi	–		Y	Exercise, low + high intensity counted separately		h per week	
71	Satisfiers	Economic security	S	M-M	–			Subjective satisfiaction with safety net, earnings after job loss		0-10, dimensionless	
72	Satisfiers	Emotional security	S	M-M	–			Subjective evaluation of emotional support in cummunity, and		0-10, dimensionless	
73	Satisfiers	Unemployment rate	O	Ma	–			Persons not working and actively searching for work		%	
74	Satisfiers	Education outcome	O	Ma	–			% with high-school diploma		0-100, dimensionless	
75	Satisfiers	Education outcome	O	Ma	–			PISA score		dimensionless, mean 500, SD	
76	Satisfiers	Education means	O	Ma	–			Expected schooling, age 5-39		years	
77	Satisfiers	Education quality	O	Ma	–			SPI country ranking for "Access to advanded education"		dimensionless, 1-168	
78	Satisfiers	Stress levels and inclusiveness	O	Ma	–			SPI country ranking for "Inclusiveness"		dimensionless, 1-168	
79	Satisfiers	Country-level income and wealth inequality	O	Ma	–			Gini index of income and wealth distribution		0-1, dimensionless	
80	Satisfiers	Detachmenent from positional consuption	S	M-M	–			Percieved ability to be happy with low material consumption		0-10, dimensionless	
81	Satisfiers	Cultural participation frequency and diversity	S	Mi	–			Subjective satisfaction with one's cultural activities		0-10, dimensionless	
82	Local Environment	Clean air outdoor	O	Ma	–		Y	PM2.5, annual average		µg/m3	
83	Local Environment	Clean air outdoor	O	Ma	–		Y	Composite of other pollutants: VOCs, ozone, NO2, SO2, CO, le		0-1, dimensionless	
84	Local Environment	Clean air indoor	O	Mi	–			PM2.5, average of daily peak hour		µg/m3	
85	Local Environment	Clean air indoor	O	Mi	–			Composite of other pollutants: VOCs (esp. formaldehyde, benz		0-1, dimensionless	
86	Local Environment	Clean air indoor	O	Mi	–		Y	CO2 as pollutant and indicator of effectiveness of ventilation		ppm	
87	Local Environment	Low chemical pollution	O	Ma	–			POP concentration in water, soil, food		0-1, dimensionless	
88	Local Environment	Noise level	O	M-M	–			Respect of street noise norms, day+night			
89	Local Environment	Physiological Equivalent Temperature (PET)	O	Ma	–			PET is the air temperature at which, in a typical indoor setting (		K	
90	Local Environment	Universal Thermal Climate Index (UTCI)	O	Ma	–		Y	UTCI is a model predicting heat stress based in the energy buc		10 UTCI thermal stress catego	
91	Local Environment	Heat Index	O	Ma	–			The heat index quantifies how the combination of air temperat		K	
92	Local Environment	Green spaces - area	O	Ma	–			Green spaces per person (housing + jobs)		m2 / capita	
93	Local Environment	Quality of outdoor spaces - subjective	S	Ma	–			tbc.			
94	Local Environment	Access to green spaces for recreation	O	Ma	–		Y	People reaching or exceeding the 3-30-300 green space rule		%	
95	QoL subjective	QoL - Aesthetic beauty	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Being able to enjoy the beauty of nature	1 (not at all satisfied) - 7 (comp	
96	QoL subjective	QoL - Challenge/excitement	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having challenges and experiencing	1 (not at all satisfied) - 7 (comp	
97	QoL subjective	QoL - Change/variation	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having a varied life. Experiencing as many	1 (not at all satisfied) - 7 (comp	
98	QoL subjective	QoL - Comfort	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having a comfortable and easy daily life.	1 (not at all satisfied) - 7 (comp	
99	QoL subjective	QoL - Education	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having the opportunity to get a good	1 (not at all satisfied) - 7 (comp	
100	QoL subjective	QoL - Environmental quality	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having access to clean air, water, and	1 (not at all satisfied) - 7 (comp	
101	QoL subjective	QoL - Freedom	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Freedom and control over the course of	1 (not at all satisfied) - 7 (comp	
102	QoL subjective	QoL - Health	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Being in good health. Having access to	1 (not at all satisfied) - 7 (comp	
103	QoL subjective	QoL - Identity/self-respect	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having sufficient self-respect and being	1 (not at all satisfied) - 7 (comp	
104	QoL subjective	QoL - Leisure time	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having enough time after work and	1 (not at all satisfied) - 7 (comp	
105	QoL subjective	QoL - Material beauty	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having nice possessions in and around the	1 (not at all satisfied) - 7 (comp	
106	QoL subjective	QoL - Money/income	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having enough money to buy and to do the	1 (not at all satisfied) - 7 (comp	
107	QoL subjective	QoL - Nature/biodiversity	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Being able to enjoy natural landscapes,	1 (not at all satisfied) - 7 (comp	
108	QoL subjective	QoL - Partner and family	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having an intimate relation. Having a stable	1 (not at all satisfied) - 7 (comp	
109	QoL subjective	QoL - Privacy	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having the opportunity to be yourself, to do	1 (not at all satisfied) - 7 (comp	
110	QoL subjective	QoL - Safety	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Being safe at home and in the streets.	1 (not at all satisfied) - 7 (comp	
111	QoL subjective	QoL - Security	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Feeling attended to and cared for by others.	1 (not at all satisfied) - 7 (comp	
112	QoL subjective	QoL - Social justice	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having equal opportunities and having the	1 (not at all satisfied) - 7 (comp	
113	QoL subjective	QoL - Social relations	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having good relationships with friends,	1 (not at all satisfied) - 7 (comp	
114	QoL subjective	QoL - Spirituality/religion	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Being able to live a life with an emphasis on	1 (not at all satisfied) - 7 (comp	
115	QoL subjective	QoL - Status/recognition	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Being appreciated and respected by others.	1 (not at all satisfied) - 7 (comp	
116	QoL subjective	QoL - Work	S	Mi	–			Subjective agreement / disagreement with QoL indicator	Having or being able to find a job and being	1 (not at all satisfied) - 7 (comp	

3. Sustainable lifestyle scenarios and perceived quality of life

3.1. Introduction

To achieve rapid reductions in CO_2 emissions, change across all sectors of society is necessary (IPCC, 2023). So far, climate models have mostly focused on how reductions in CO_2 emissions can be achieved by supply-side solutions, which are often technological solutions that make the supply of energy more sustainable (IPCC, 2022). It is however becoming apparent that supply-side solutions alone are likely not sufficient to achieve rapid reductions in CO_2 emissions, and that demand-side changes are also necessary (e.g., Grübler et al., 2018). Demand-side solutions are solutions that reduce the demand for energy, goods, and services, and involve for example changes in lifestyle and more efficient use of resources (Grübler et al., 2018).

While the potential of demand-side solutions, and especially lifestyle changes, in reducing CO_2 emissions is promising (e.g., van den Berg et al., 2019), there are concerns that people's well-being and quality of life may be negatively affected by these changes. For example, smaller living spaces and more shared spaces represents an important step towards more sustainable lifestyles (e.g., Sandberg, 2021), but could thwart people's need for privacy. A recent study however inventoried the potential effects of demand-side solutions on well-being, and found that across the board, demand-side solutions are compatible with high levels of well-being (Creutzig et al., 2021). Importantly, this study specifically focused on examining how demand-side solutions are associated with objective indicators that determine well-being, such as air quality, access to sufficient and safe food, and exposure to crime (Creutzig et al., 2021).

In addition to such objective indicators of well-being, people also hold a subjective evaluation of their well-being (e.g., Ryan & Deci, 2001; Oswald & Wu, 2010). So far, studies have not yet systematically examined how people's subjective well-being relates to demand-side solutions. Yet, studying how subjective well-being is affected by demand-side solutions is critical for two reasons. First, people's subjective evaluations of their own well-being are often correlated with objective indicators, but do not completely overlap (e.g., Oswald & Wu, 2010). People's subjective perceptions of their own well-being thus hold information that is not accounted for fully by objective indicators - subjective evaluations typically matter more.

Second, people's expectation of how their well-being is affected by lifestyle changes may not necessarily align with their actual experience. For example, studies have found that people often oppose environmental policies strongly before they are implemented, but are more positive in their evaluation after the policy has been in place for some time (van Wee et al., 2023). Critically, the anticipation of a decrease in well-being can result in resistance and a lack of support for sustainable policies, reducing the political mandate necessary to implement them (e.g., Vonk Noordgraaf et al., 2014; Bergquist et al., 2022; Anderson et al., 2017). Understanding when and why people anticipate that their well-being will be negatively affected is thus critical to ensure policies are designed and introduced in such a way that they engender the least amount of resistance and can be implemented successfully.

In this study, we therefore aim to examine how people evaluate a scenario that showcases what life looks like in the future where many demand-side changes are implemented. We specifically assess how people expect their quality of life will change under this scenario, and how this in turn relates to their acceptability of the scenario.

Quality of life is a concept that is closely related to the concept of well-being, and is used among others by the WHO to examine how people evaluate their position in life (Skevington & Böhnke, 2018). Quality of life research specifically assesses how people evaluate different important domains that together make up people's overall life experience, such as people's health, social connections, and environmental quality in their place of residence (e.g., WHO, 2012). This approach thus gives a specific insight into which domains people expect demand-side solutions or lifestyle changes to enhance or reduce their quality of life. In addition, quality of life measures can be used to assess which domains people find most important in life (see Poortinga et al., 2004). This approach can thus help us to understand better when and why people find demand-side changes more or less acceptable. Specifically, we expect that people will find the scenario less acceptable if they perceive that it negatively affects those quality of life domains that people find most important.

3.2. Methods

3.2.1. Participants and procedure

Participants for this study were collected via three different approaches. First, 235 first-year psychology students were recruited for participation via SONA, a student participants pool of the University of Groningen. These students completed the questionnaire online and received course credits as compensation for their time. Second, 199 students from the faculty of economics and business completed the questionnaire as part of a series of studies that were completed in the lab on location. Participants received €10 for their participation in the study. Lastly, 250 members of the Dutch general public participated in the study via Prolific.co. Participants completed the survey online and received £2 for participating. The part of the study conducted with students was exempted from ethical review by the ethics committee of the University of Groningen, as it is a low-risk study. The part of the study conducted via Prolific.co was reviewed and approved by the ethics committee of the University of Groningen. We discuss the findings of the 3 participants groups simultaneously (total n = 681, after removing incomplete responses and failed attention check, see below).

The study was completed digitally in Qualtrics and could be completed in Dutch or English. Participants first read an informed consent form and indicated their consent to participate. Next, participants were asked to indicate their current level of life satisfaction, and to indicate how important they find 15 different quality of life domains for their own well-being. Participants then watched a video (length 2:41) produced by the Dutch Youth Climate Movement. The video features an animation and narrated voice-over (in Dutch, English subtitles were provided) that describes life in the Netherlands in the year 2040. This video showcases a scenario that introduces many demand-side solutions to climate change, including working fewer hours, circular economy, purchasing fewer items, car-free cities, smaller homes, sharing economy, shifts to a plant-based diet, and flying less. Participants then completed an attention check to ensure they saw the video (4 participants were removed for failing the attention check). Next, participants indicated how acceptable they find the scenario, how acceptable they think

others find the scenario on average, and how feasible they find the scenario. Then participants evaluated how they expect their quality of life to change if the scenario was implemented. The order of these blocks of items was counterbalanced: people randomly either completed the acceptability items or the quality of life items first. The survey ended with questions assessing people's climate change perceptions and demographic information. In this report, we specifically focus on how people think the scenario will affect their quality of life, and how acceptable they find the scenario.

3.2.1. Measures

Quality of life - importance. Participants were presented with a list of 15 quality of life domains including a label and a description (see Table 1). Participants indicated how important they find each domain to their overall quality of life using a 5-point Likert scale ranging from 1 (not at all important) to 5 (very important). The 15 quality of life domains were adapted from Poortinga et al. (2004), who present a list of 22 domains. To ensure the domains were relevant for this study and to keep the questionnaire as brief as possible, we selected from and adjusted the domains provided by Poortinga et al. (2004) as follows. We adopted the following 12 domains without alteration or with only minor adjustments to the description in order to improve comprehension among our participations: health, comfort, environmental quality, freedom, identity and self-respect, free time, money and income, nature and biodiversity, social relations, privacy, safety, social justice. We combined challenge/excitement and change/variation into one domain we label Fun ('doing fun and varied activities in daily life'). We combine work and education into one item we label Work and Education ('The possibility to find or perform work or education that fits well with your interests and skills.). We excluded the following 6 domains as they were already addressed in other domains or not directly relevant to the demand-side solutions depicted in the scenario: aesthetic beauty, material beauty, partner and family, security, spirituality/religion, and status/recognition. Lastly, we added one final domain to our list that covers the quality of the living environment ('An aesthetically pleasing and nice living environment.').

Quality of life - expected changes. After watching the video showcasing the scenario, participants were asked to respond on a 7-point Likert scale to the following question: If I would live my life as described in the video, my quality of life would ... become much worse (1), become moderately worse (2), become a little bit worse (3), stay the same (4), become a little bit better (5), become moderately better (6), become much better (7). Then, for the same 15 quality of life domains as mentioned above (see Table 1), participants indicate how they expect each domain to change if they would live their life as presented in the scenario. Perceived changes in quality of life were assessed with a 7-point Likert scale (1 = become much worse, 4 = stay the same, 7 = become much better).

Acceptability. Acceptability of the scenario was assessed using the following four items: I think the lifestyle presented in this video is … totally unacceptable (1) – very acceptable (7), not good at all (1) - very good (7), very negative (1) – very positive (7), not at all necessary (1) – very necessary (7) (based on Liu et al., 2019). Responses across the four items were averaged to create an overall scale for acceptability (M = 5.70 SD = 1.29, α = .94).

Table 1
Quality of life domains assessed in this study

Label	*Description*
Health	Good physical and mental health. Having access to healthcare
Living environment	An aesthetically pleasing and nice living environment.
Fun	Doing fun and varied activities in daily life
Comfort	Having a comfortable and easy daily life.
Work and education	The possibility to find or perform work or education that fits well with your interests and skills.
Environmental quality	Living in an environment with clean water, clean air, and no ground pollution. No or minimal exposure to harmful substances in daily life.
Freedom	Freedom and control over the course of one's life, to be able to decide for yourself, what you do, when, and how
Identity and self-respect	Having sufficient self-respect and being able to develop one's own identity.
Free time	Having enough time off to do things after work and other responsibilities
Money and income	Having enough money to buy and to do the things that are necessary and pleasing.
Nature and biodiversity	Assurance of the continued existence of plants and animals, maintaining biodiversity. Being able to enjoy natural landscapes, parks, and forests.
Social relations	Having good social relations with family, friends, colleagues, and neighbors. Being able to maintain these contacts and make new ones.
Privacy	Having the opportunity to have a place of your own, to do your own things
Safety	Being safe in and outside the home
Social justice	Having equal opportunities and having the same possibilities and rights as others. Being treated in a righteous way.

3.3. Results

3.3.1. Importance of quality of life domains

Across the board, all quality of life domains were on average rated as at least somewhat important. On average, people found health (M = 4.70), safety (M = 4.56), and freedom (M = 4.36) the most important quality of life domains for their own well-being. People found nature and biodiversity (M = 3.73), comfort (M = 3.84), and living environment (M = 3.99) the least important quality of life domains. An overview of the average importance of each domain is presented in Figure 1.

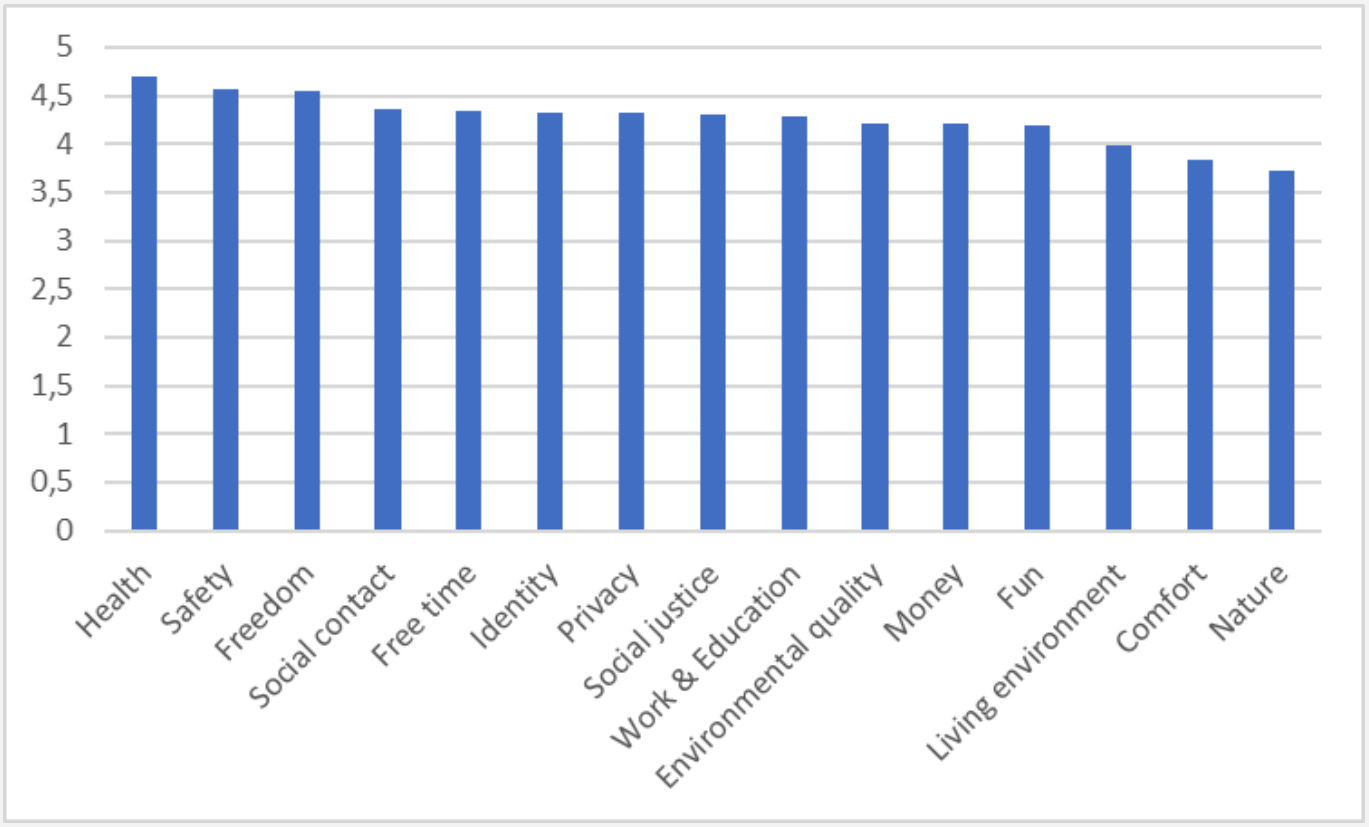


Figure 1. An overview of how important on average respondents found each quality of life domain for their own well-being on a scale from 1 (not important at all) to 5 (very important).

3.3.2. How is quality of life perceived to be impacted by the scenario?

Overall, most people expect that their quality of life would increase if they lived their life as described in the scenario: a total of 72% of respondents indicate their quality of life would be better under the scenario, 11.4% indicates their quality of life would stay the same, while 16.7% expect their quality of life to decrease under the scenario.

We next examine how people expect each of the individual quality of life domains to change (see Figure 3). On average, people expect that the following domains will become better (M > 5): nature and biodiversity (M = 6.45), environmental quality (M = 6.42), living environment (M = 5.88), health (M = 5.45), and free time (M = 5.12). People expect no changes in the domains of fun (M = 4.54), comfort (M = 4.47), work and education (M = 4.49), identity and self-respect (M = 4.43), social connections (M =

4.78), safety (4.75), and social justice. People expect the following domains will become slightly worse (M < 4): money and income (M = 3.80), privacy (M = 3.92), and freedom (M = 3.95).

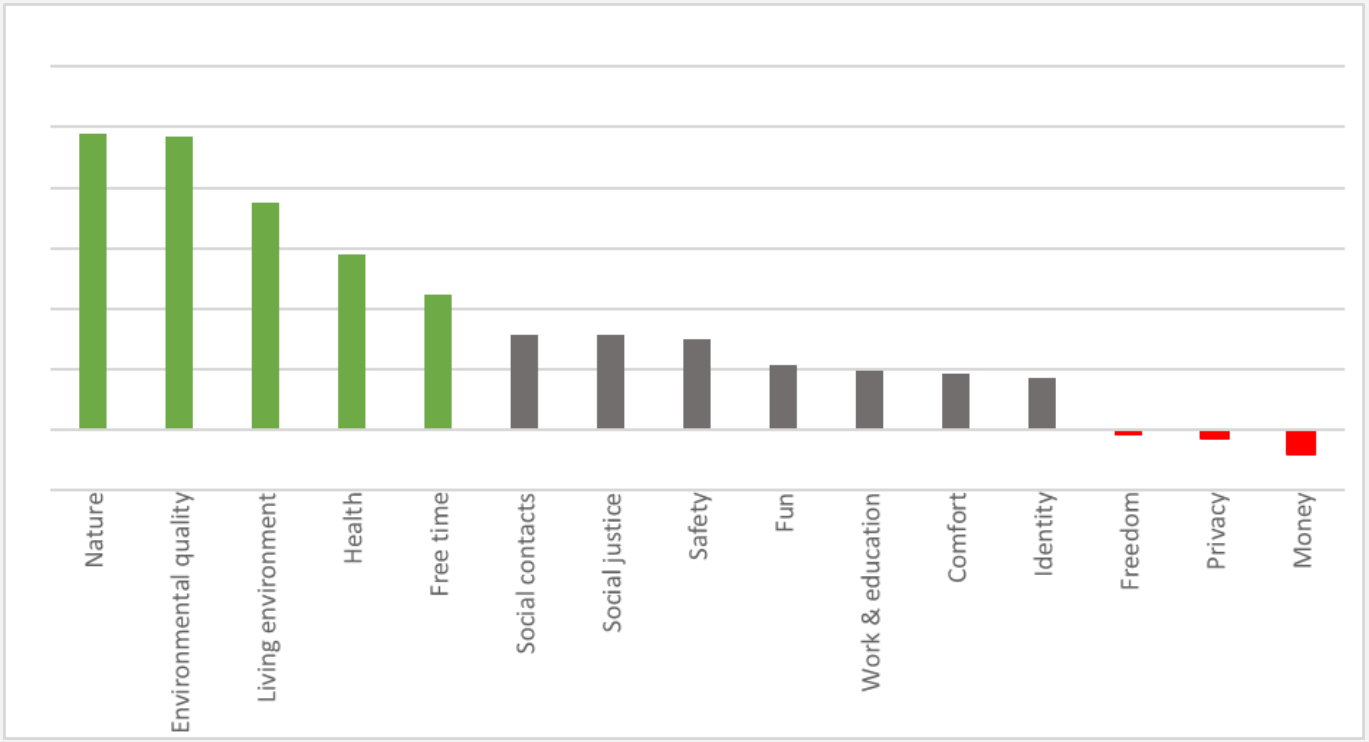


Figure 2. An overview of how participants expect the Quality of Life domains would be positively (green), negatively (red), or not (gray) affected if they would live their life as presented in the scenario.

3.3.3. Acceptability of the scenario

On average, most people found the scenario highly acceptable, with the acceptability of the scenario rated an average of 5.7 on a 7-point scale. A total of 81% of participants found the scenario acceptable, 9% had a neutral evaluation of the scenario, and 10% found the scenario unacceptable. To better understand why people do or do not find the scenario acceptable, we examine differences between people who rated the scenario as unacceptable (acceptability < 4, n = 68) and participants who rated the scenario as acceptable (acceptability > 4, n = 552). Specifically, we examine which quality of life domains these participants find most important, and which domains they think will be most changed under the scenario.

Figure 3 and Figure 4 present an overview of how important each group found each quality of life domain, and which changes they expect to happen to the quality of life domains under the scenarios. Interestingly, both groups found health, freedom, and safety the most important domains. The group that found the scenario unacceptable expected the domains freedom, money and income, privacy, fun, and identity to worsen under the scenario. An especially big decrease in quality of life was expected in the domain of freedom, which is also a domain which this group found highly important. They also expect an increase in the domains of nature and biodiversity and environmental quality, but these are both domains which are relatively unimportant to this group.

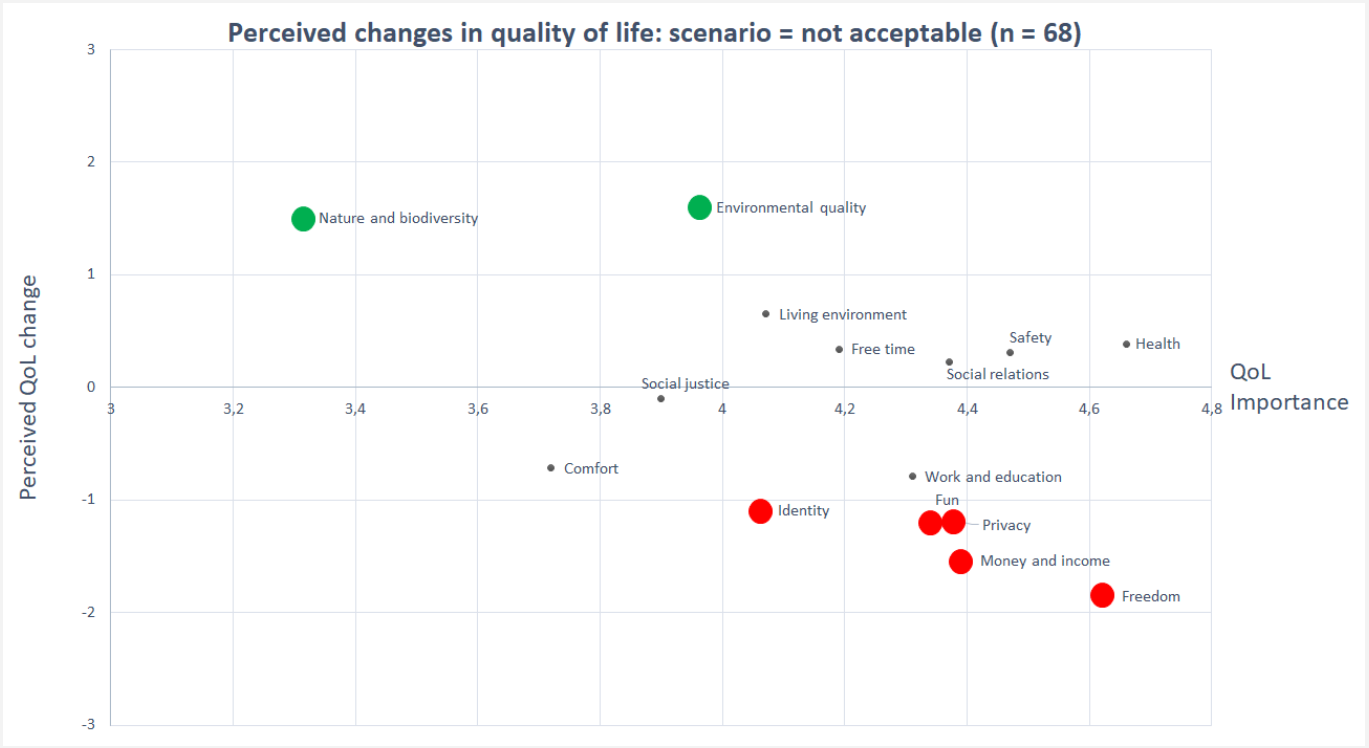


Figure 3. Overview of how important participants who did not find the scenario acceptable find different quality of life domains (x axis) and which quality of life domains they expect to improve (green) and worsen (red) under the scenario (y axis).

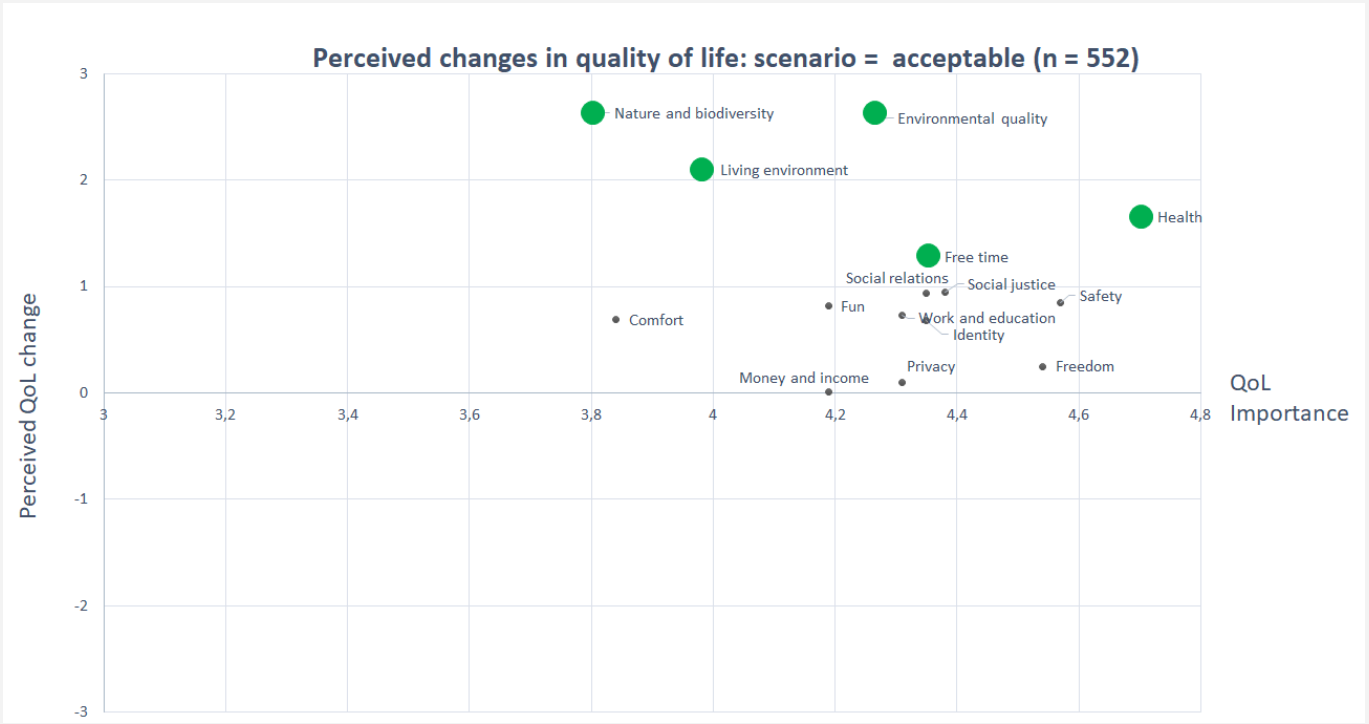


Figure 4. Overview of how important participants who found the scenario acceptable find different quality of life domains (x axis) and which quality of life domains they expect to improve (green) and worsen (red) under the scenario (y axis).

The group who found the scenario acceptable did not expect there would be any negative impacts to the quality of life domains, a notable difference with the group who found the scenario unacceptable. They also perceived an increase in the domains of health, free time, environmental quality, living environment and nature and sustainability. Another important difference between the groups lies in the perceptions of the quality of life domain of health, which was the most highly valued out of all domains. The participants who evaluated the scenario as acceptable expected an increase in the domain of health, whereas the participants who evaluated the scenario as unacceptable did not think the domain of health would change.

3.4. Discussion

Demand-side solutions represent an important strategy to reduce CO_2 emissions and are compatible with high-levels of well-being. Yet, current investigations of demand-side policies have focused on objective indicators of well-being, and it is therefore not clear how people subjectively evaluate demand-side policies. Yet, if people perceive demand-side solutions as worsening their quality of life, this could lead to resistance, which lowers the political mandate needed to implement demand-side policies. It is therefore important to know how people perceive demand-side solutions and why people find such policies (not) acceptable.

In this study, we presented a video to people showcasing a scenario that introduced a variety of demand-side policies, and asked for their opinions on how they expect this scenario would affect their quality of life, as well as how acceptable they found the scenario. Our findings offer a first systematic examination of how people respond to a scenario where demand-side solutions are introduced, yielding two critical main insights.

First, we found that the scenario in our study was evaluated very positively. The vast majority of respondents (72%) expected that their quality of life would increase under the scenario, which is in line with scientific assessments that have found that demand-side solutions are compatible with high levels of well-being. Even more participants (81% of respondents) rated the scenario as acceptable, which indicates they find the scenario good, necessary, useful and acceptable. As the scenario used in the study bears close resemblance to the EDITS LED and High with Low scenarios, this gives a first indication that people may in general perceive such scenarios based on demand-side solutions as a desirable solution to climate change, and that the political mandate to implement such policies may be higher than expected. In general, these findings track with recent studies that have found that support for climate policies is generally high across the globe, and that there is a tendency to underestimate the support for climate policies (see for example Andre, Boneva, Chopra, & Falk, 2024).

Second, our findings also shed light on why people do not find the scenario acceptable. While this group represents a minority in the current study, previous research has found that particularly opponents of a policy or measure are motivated to voice their opposition or protest the implementation of a measure (e.g. Liu, Perlaviciute & Squintani, 2022). This minority group may thus be particularly vocal and powerful in expressing resistance to demand-side solutions, which may make it seem that the political mandate for implementing policies is much lower than it is in practice. Our results indicate that people who did not find the scenario acceptable still had a relatively nuanced evaluation of its impacts. For example, they did expect that the domains of environmental quality and nature and biodiversity

would increase under the scenario. However, they particularly anticipated a decrease in highly-valued quality of life domains, which include freedom, money and income, and privacy. These findings indicate that any communication surrounding demand-side solutions, particularly those aimed at including opponents of these policies in the conversation, should take into consideration that this group feels that very important quality of life domains are threatened, and they will therefore likely feel strong emotions and concern about the scenario. Based on our findings, communicators can develop strategies that accurately acknowledge these concerns, and find possible ways to address them.

We will further advance this line of research in two ways. In the short-term, we are currently preparing a cross-cultural replication of this study in collaboration with EDITS-member Prof. Dr. Masahiro Sugiyama. The cross-cultural replication will specifically take place in Japan and India, and will aim to examine the extent to which the findings of our initial study are generalizable to other cultural contexts. Once the data collection for the cross-cultural replication has been completed, we will write up the joint results of this work for a journal article.

Second, we will use the basic methodology we have developed here in the new EDITS fast-track programme ‘WELL-with-LOW - Wellbeing Metrics and Assessment of LED-type Policy Options”. Specifically, this fast-track will consist of the development of a tool that allows users to examine the influence of supply- and demand-side policies on CO_2 reductions as well as on objective indicators of well-being. We will use the methodology introduced here to examine people’s responses to this tool, specifically examining when and why people prefer supply- or demand-side policies, what impacts they expect these policies to have on their quality of life, and to examine which information should be presented (and how) in order to achieve support (or lower resistance) to demand-side policies.

4. Systems perspectives on transforming Swiss housing

4.1. Context of the project

In collaboration with, and as part of the Swiss SWEET-SWICE project (sweet-swice.ch), or Sustainable Wellbeing for the Individual and the Collectivity in the Energy transition, Sascha Nick developed an "Alternative provisioning framework for the Swiss habitat for wellbeing with smaller resource footprint", and presented the main findings in the EDITS Annual Meeting 2023, as described in section "1.2.3. Wellbeing at the EDITS Annual Meeting 2023" above.

Following the conference, this work was developed into a scientific paper, which was submitted on 23.01.2024 to Frontiers in Sustainability under the title: "Systems perspectives on transforming Swiss housing by 2040: wellbeing, shared spaces, sufficiency, and de-sprawl".

Abstract

The Swiss habitat – buildings and related mobility – is facing multiple wicked problems that can only be solved together, such as high energy use and climate impact, high material use with low circularity, accelerating urban sprawl and ecosystem destruction, high mobility costs, low inclusion, and mixed wellbeing outcomes. Action levers, coordinated efforts on multiple system leverage points, are here combined with rethinking needs satisfiers and provisioning. We model the effect of a country-wide new building moratorium until 2100; with four simultaneous neighborhood-scale renovations to energy class "A" and high indoor environmental quality, flexible shared living spaces, availability of all essential daily services in each neighborhood, deconstructing unneeded settlements; as well as renovation labor availability and productivity. Results are highly promising, suggesting full renovation is feasible in 14-20 years while reducing labor, energy, materials, and costs during and after the transition, and reversing urban sprawl to its level in 1935 or even 1885, depending on deconstruction choices. This suggests possible low-risk demand-side policies, simultaneously improving wellbeing, energy resilience, biodiversity, and climate impact - as a basis for societal dialogue and experimentation.

As the paper is currently in review, the full text cannot be reproduced here; only the methodology is summarized below, and the main elements of the EDITS Annual Meeting presentation are reproduced.

4.2. Methodology

First, based on scientific literature, a systems perspective is analyzed at three levels:

1. Stocks and flows: energy, materials, buildings, floor space, worker availability and productivity, renovation rates, urban sprawl, ecosystems, and various dimensions of human wellbeing
2. Positive and negative feedback loops: energy efficiency and rebound effects; demand, supply and volatility of housing as an asset class; urban sprawl and car lock-in, political mobilization for sufficiency
3. Leverage points and action levers: exploring combined action on multiple high leverage points, especially mindset (#2), system goal (#3), power to change system structure (#4), and system rules (#5)

Second, a model was developed, covering most aspects of stocks and flows described above, and a number of scenarios tested.

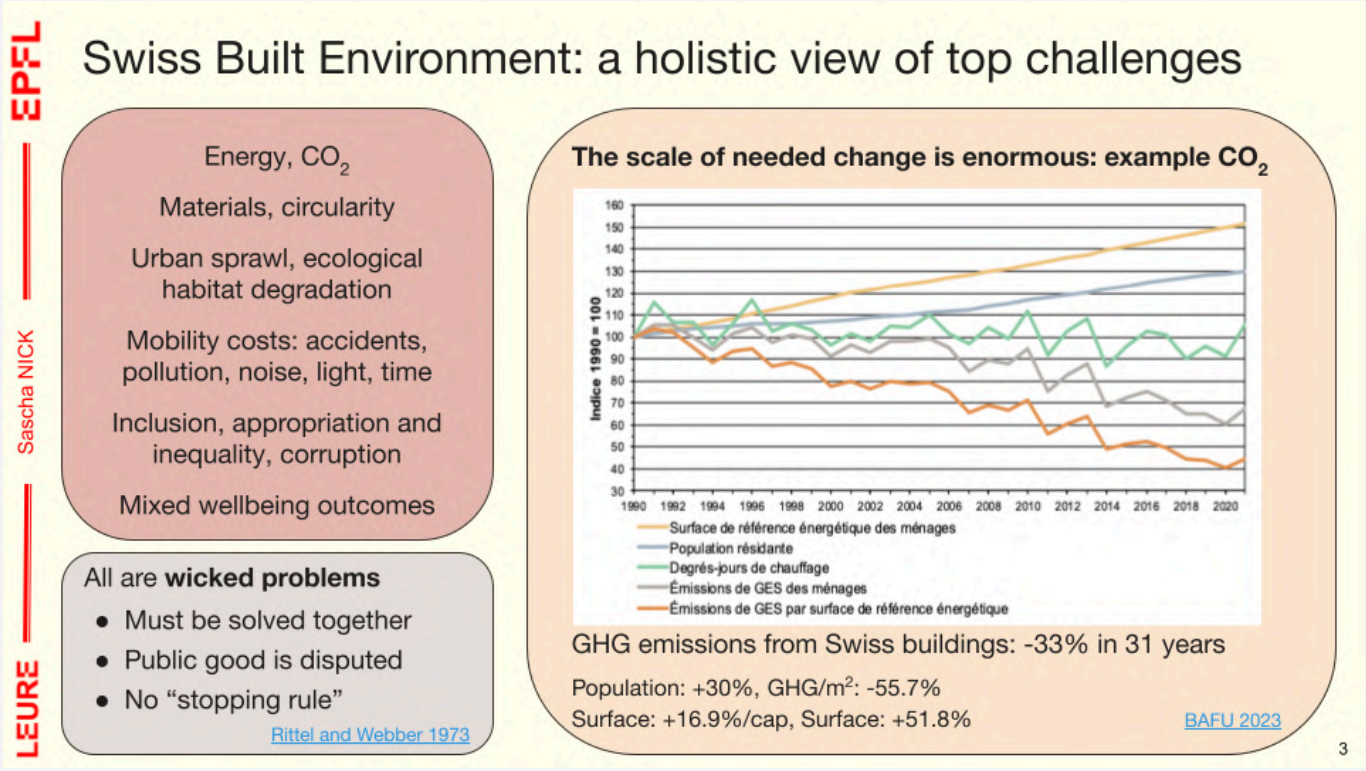
Third, an analytical model of urban de-sprawl was developed, and linked to the output of the model above, to estimate a potential level of de-sprawl depending on the scenario.

Fourth, based on results of the three steps above and literature, policy implications are discussed, and a research agenda is proposed to close the remaining gaps.

4.3. Results

(The main elements of the EDITS Annual Meeting presentation are reproduced here)

There are multiple interrelated challenges of the Swiss build environment, which can be seen as wicked problems, and they can only be solved together. Energy efficiency renovations are a good example, as 30 years of investment and a very supportive public policy with multiple subsidy schemes have achieved an average reduction of CO_2 emissions per m^2 of 56%, yet at the same time with population growth and an increase of surface per capita, the overall effect has been much smaller.



We define eudaimonic wellbeing as a state of thriving, based on full participation in society, and the pre-condition of all needs being satisfied. As in the example on the chart below, needs are universal and unchanging, whereas satisfiers are culturally specific. Here we focus on the universal goal of **participation**, with **health** and **autonomy** as basic needs. To satisfy all three, we look for synergistic satisfiers.

Wellbeing, sufficiency, synergistic satisfiers

Sustainable wellbeing extends to future generations, respects ecological constraints

Eudaimonic wellbeing: a state of thriving, full participation in society, a sense of leading a good life

Precondition: all needs being satisfied

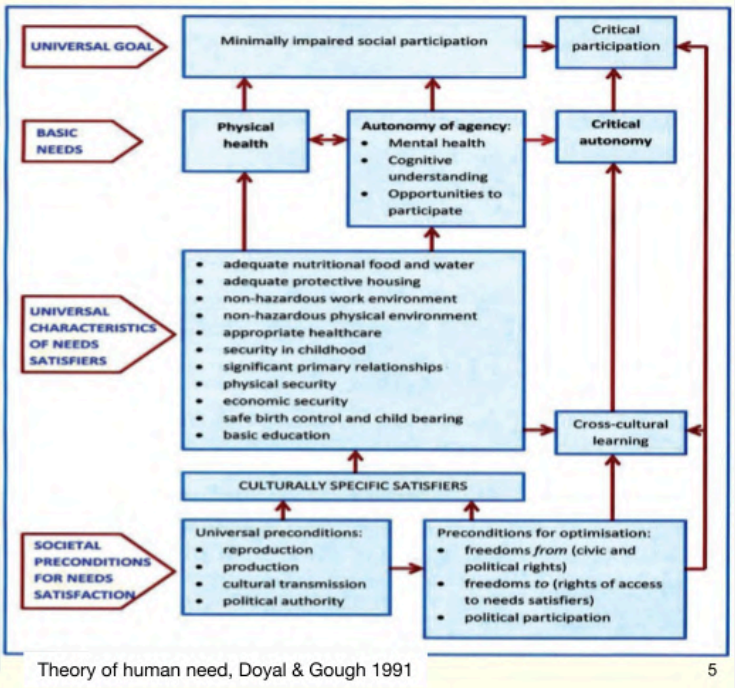
Needs: universal, unchanging, satiable

Satisfiers: culturally specific

Types: inhibitors, pseudo-, simple, synergistic satisfiers

Sufficiency as organizing principle of society

→ focus on synergistic satisfiers



Theory of human need, Doyal & Gough 1991

5

On such synergistic satisfier are shared spaces, which can satisfy the needs for participation, creation, understanding, and identity. First, most spaces are empty most of the time, which is wasteful. Second, shared spaces allow a combination of low-barrier participation and privacy when needed, thus satisfying multiple needs using the same resources. By reducing the size of private spaces and sharing most of the spaces (either using together, like shared kitchens, or reserving sequential exclusive use, like meeting or guest rooms), the utility can be improved and the total space significantly reduced, in the case of Switzerland by around half.

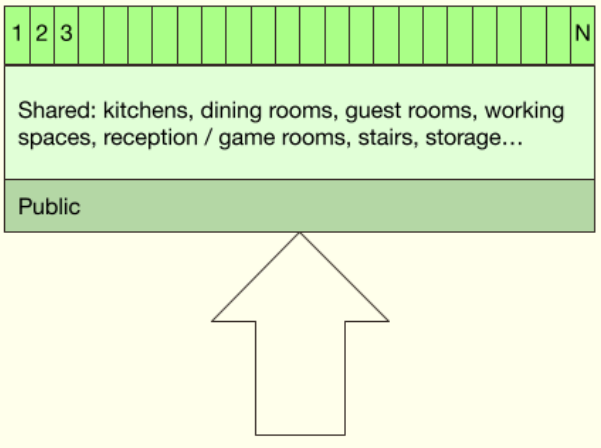
Example: shared spaces, human needs perspective

Shared spaces as synergistic satisfier for participation, creation, understanding, identity

CH 2020 habitable space per person: 46.6 m^2 (plus 9.3 m^2 shared and 3 m^2 secondary residences);
Public / non-habitable space per person: 14.6 m^2 (total 73.5 m^2)

2020 Private+Shared+Public, N people

2040 Private+Shared+Public, N people



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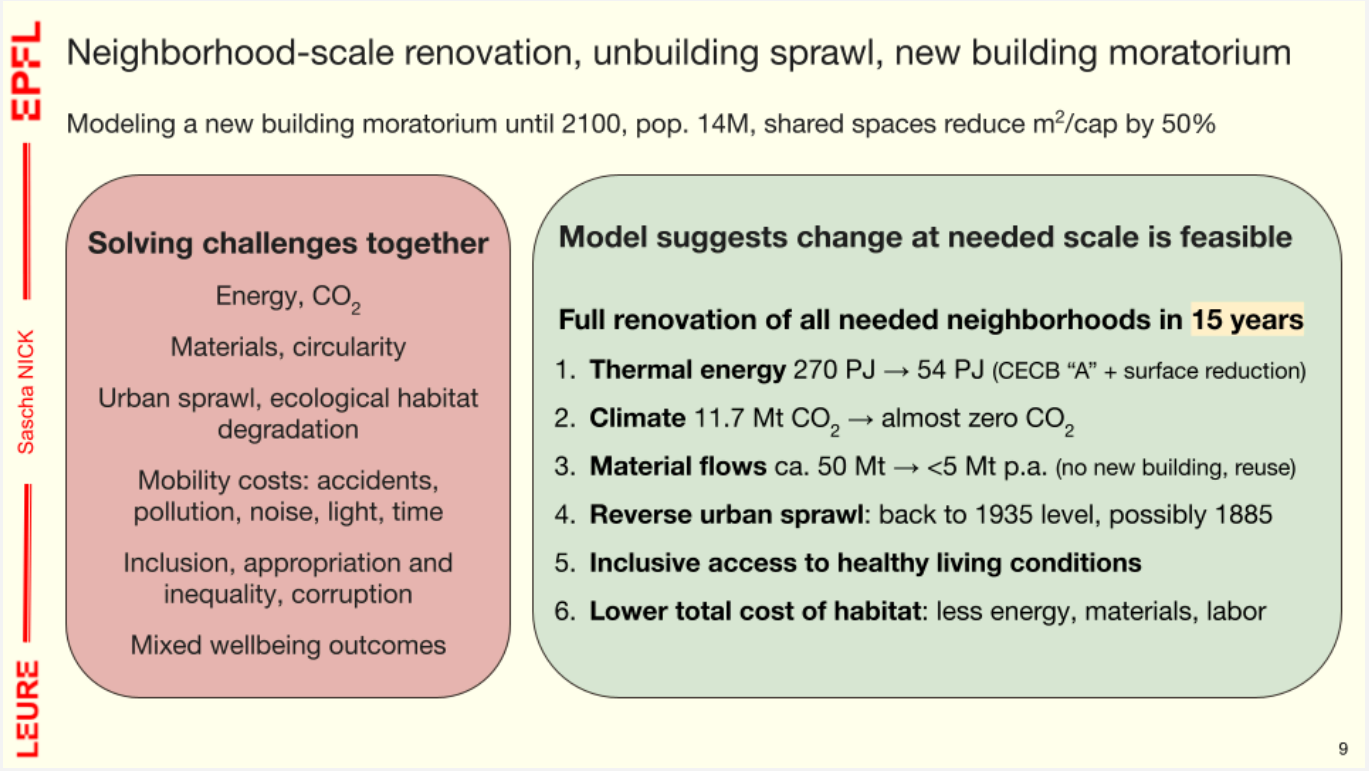
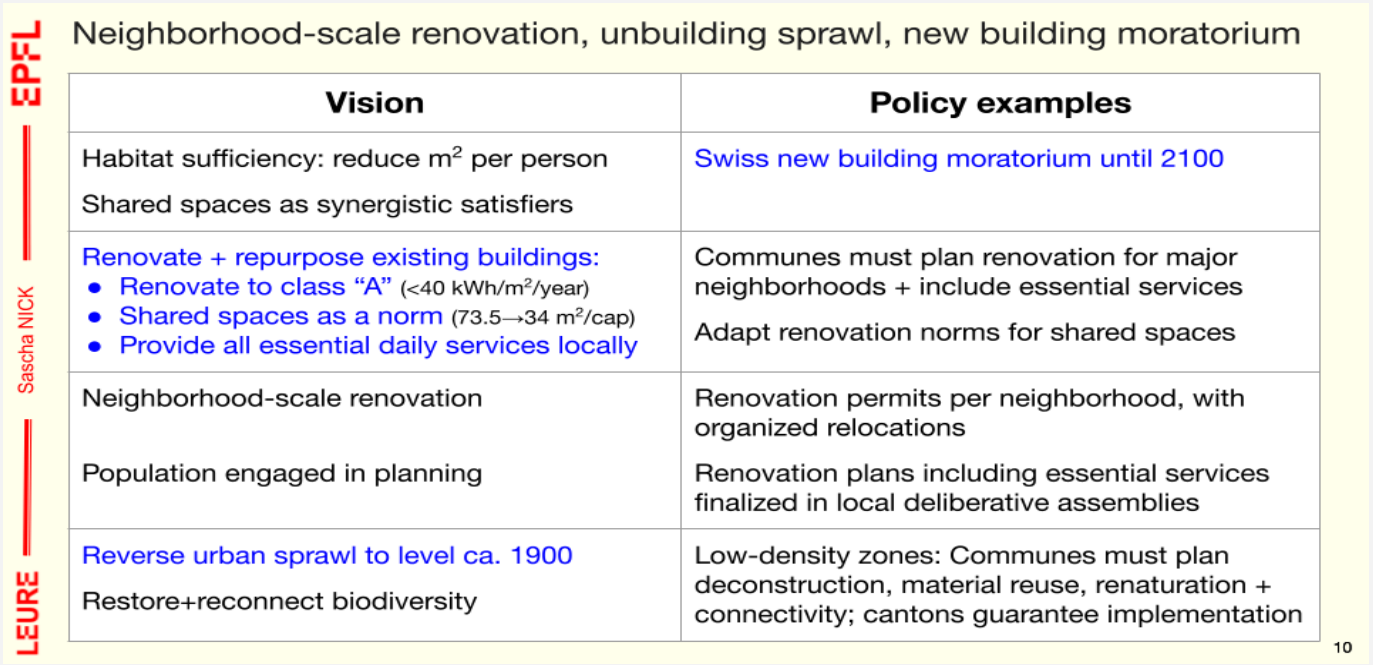
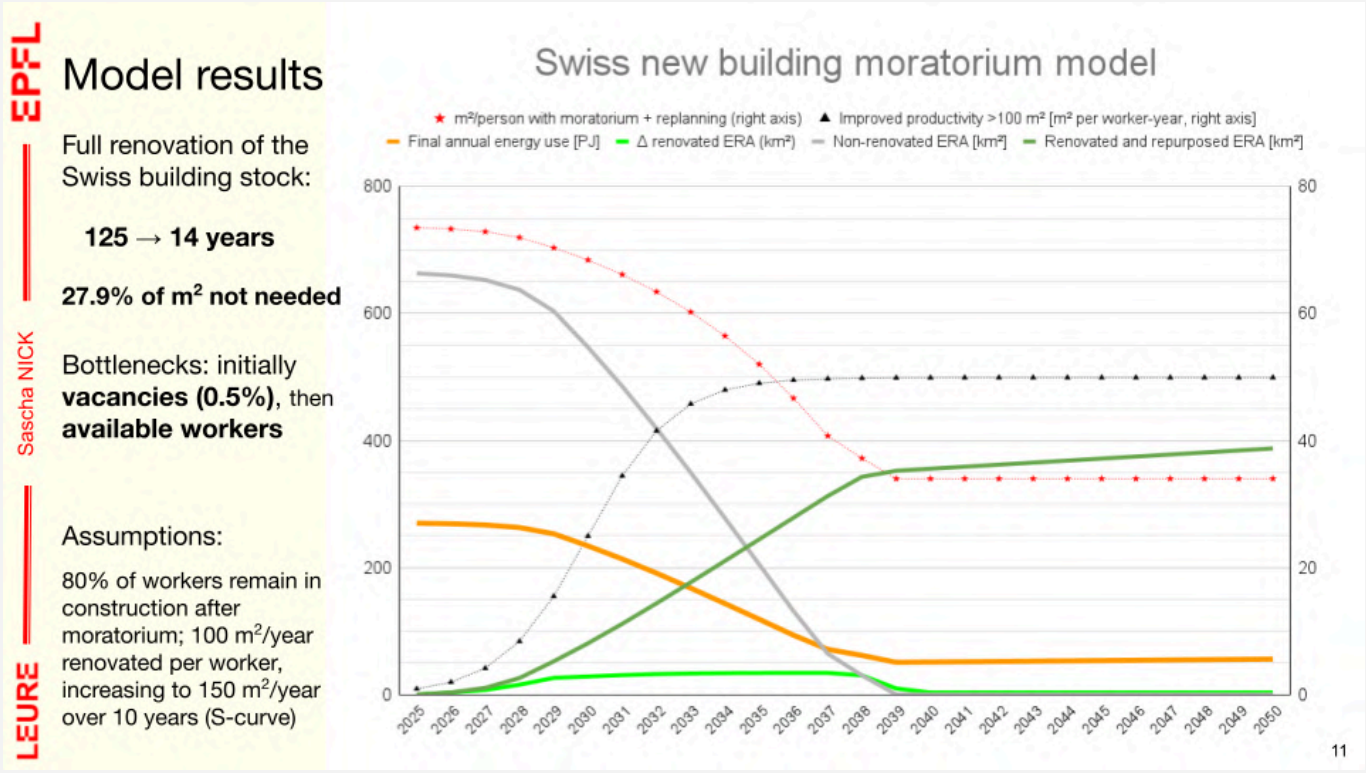
Finding skilled labor to do the needed renovations is a challenge in Switzerland, but as based on the simulation, there are more than enough buildings to cover Swiss housing needs well beyond 2100, we here propose a country-wide new building moratorium (effectively transferring 200k skilled workers, engineers, and architects to renovation), neighborhood-scale renovations (more efficient, less disruption, and the ability to re-think local services and reduce the need for mobility), and at the same time deconstructing unneeded buildings (reusing materials, reducing urban sprawl). On this basis, the simulation results are very promising.



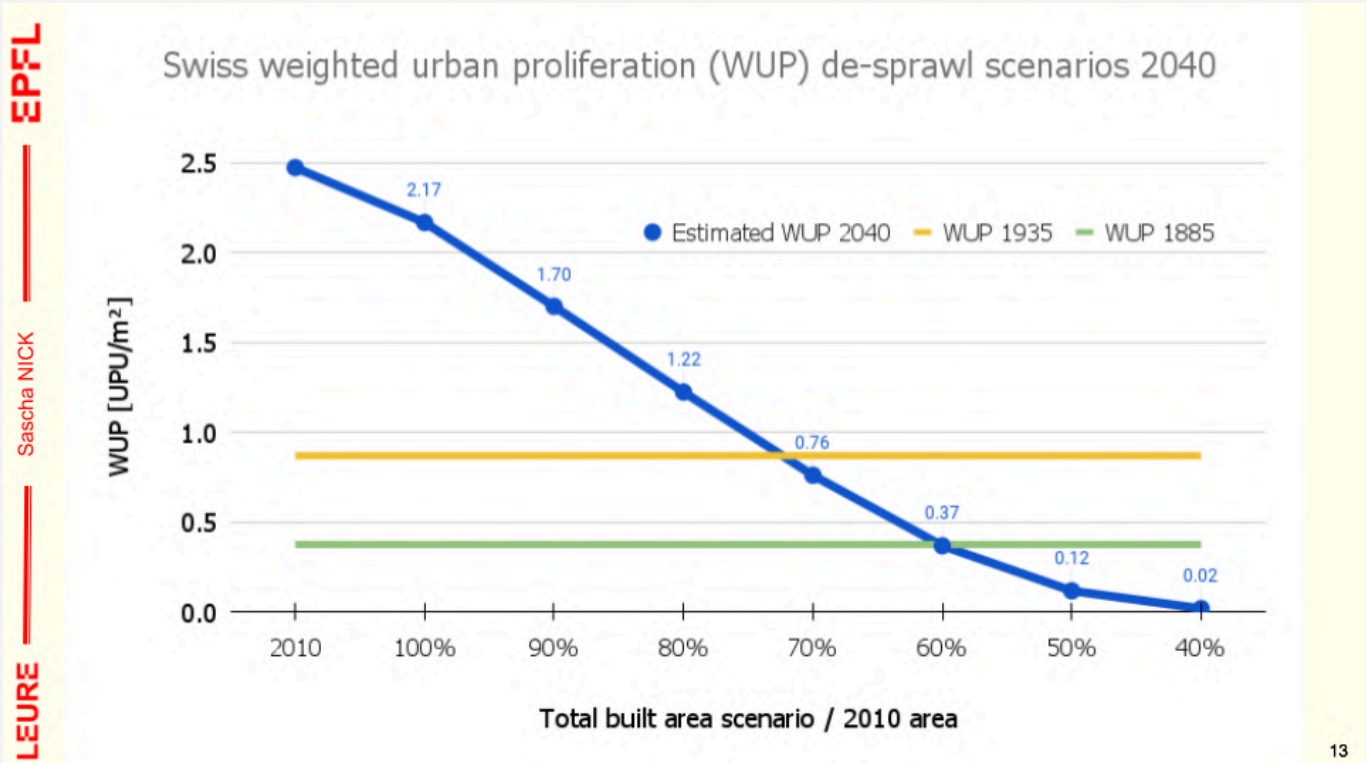
Then we explore public policy options needed to create favorable conditions:



Combining all previous elements, we simulate the moratorium with neighborhood-scale renovation, and show the full renovation of all needed buildings is possible in just 14 years (2025-2039), accelerating renovations by a factor of five or six from baseline, ensuring high quality housing for all, and reducing aggregate final energy use by a factor of five - for high wellbeing with low energy use.



Finally, we explore the impact on reducing urban sprawl: based on 27% unneeded floor area, we keep between 73% of total built area (if random deconstruction) and 60% (if optimized), corresponding to turning back urban sprawl to its level in 1930 and 1885 respectively.



5. Final remarks / connection to other EDITS activities

In addition to pursuing the wellbeing projects described in the previous chapters, WG4 Wellbeing will support several recently approved fast-track projects, and build upon and contribute to work by members of the EDITS network.

In particular, FT1 "WELL-with-LOW - Wellbeing Metrics and Assessment of LED-type Policy Options" directly aligns with the focus of WG4 Wellbeing; we plan for close collaboration.

As an rapid summary of work by members of the EDITS network related to wellbeing, we wish to cite:

- Within the project IIASA SI Just Transitions to Net-zero Carbon Emissions for All (JustTrans4ALL), several EDITS colleagues (i.e., Elina Brutschin, Jarmo Kikstra, Jihoon Min, Shonali Pachauri, Caroline Zimm) under the lead of IIASA researchers Roman Hoffman and Omkar Patange have submitted a manuscript to Nature Communications: “Hoffmann, R., Patange, O., et al. Decent living standards beyond reach for many despite ambitions to leave no one behind”. The paper looks at the achievement of Decent living standards at subregional level over time for around 70 developing countries. As a next step, the group aims to bring these insights into energy/mitigation scenarios.
- Miyuki Nagashima has joined Smart City Institute Japan, to establish a link with the Liveable Wellbeing City Indicator, and is supporting WG4 Wellbeing by providing insights from this project and helping translate the results, mostly available only in Japanese. In this model, wellbeing is defined as an interplay of (i) the Living environment, (ii) Relationships in the region, and (iii) Staying true to oneself. All three can be measured subjectively (ca. 50 questions) and objectively (ca. 200 indicators).
- Benigna Boza-Kiss wrote a section in the Austrian Assessment Report in Chapter 5 on wellbeing, informed by the work done in EDITS. It provides a review of measures (qualitative and quantitative) of wellbeing and good life in Austria, with a linkage to the provisioning systems.
- Nuno Bento organized the 2023 EDITS Annual Conference that highlighted the need to dig in deeper in the determinants of well-being and in the different means of minimum standards of living according to the spatial context (global south vs. north, intermediate countries,...), and also contributed to the understanding on how technological innovations in digital convergence and sharing can help to improve lives with benefits for the fight against climate change.
- Masahiro Sugiyama adapted for Japan, and later India, a survey on wellbeing based on the survey about the LED / HwL scenario in the Netherlands, developed by Linda Steg and Anne van Valkengoed, and described in detail in Chapter 3.
- Yannik Stuka, Elina Brutschin, Shonali Pachauri, Massimo Tavoni, LaraAleluia Reis, and Johannes Emmerling are writing a working paper “Assessing wellbeing in the context of global Integrated Assessment Models” (preliminary title). The paper introduces a novel framework to assess scenarios from a wellbeing perspective, covering health (air pollution, water access, global warming effects), decent living standards (access to essential services: mobility, energy, food), and security (effect of energy policy on trade patterns and employment shifts); and explores challenges in incorporating multidimensional wellbeing into global integrated assessment models.
- Carina Zell-Ziegler and Johannes Thema are working on a feasibility assessment of a range of possible sufficiency policies in the mobility sector, including acceptance and wellbeing factors.

Additionally, all three sectoral Working Groups (Buildings, Transport, and Industry) have included aspects of wellbeing in their work, in various stages of the publication process. As an illustration of this work (more details in the sectoral WG reports), the Buildings Working Group developed the following results relate to wellbeing:

- Buildings are key in supporting human activities and wellbeing by providing shelter and other important services to their users. Buildings are, however, also responsible for major energy use and greenhouse gas (GHG) emissions during their life cycle. The paper reviews a range of building sector models to – among others – find how they capture decent living standards. This review provides recommendations on the model developments needed to better understand LED transformations in buildings and support decision-making towards sustainability targets.
    - Source: Mastrucci, Alessio, Leila Niamir, Benigna Boza-Kiss, Nuno Bento, Dominik Wiedenhofer, Jan Streeck, Shonali Pachauri, et al. 2023. “Modeling Low Energy Demand Futures for Buildings: Current State and Research Needs.” Annual Review of Environment and Resources 48 (1): 761–92. doi.org/10.1146/annurev-environ-112321-102921
- The paper reviews modeling the industrial system for Low Energy and Materials Demand (LEMD) futures, to understand how supply- and demand-side measures affect – among many others - service provisioning supporting societal wellbeing It calls for strengthening interdisciplinary collaborations between industry modeling traditions and demand-side research, to produce more insightful scenarios and discuss research challenges and recommendations.
    - Source: Material Cycles, Industry and Service Provisioning: A Review of Low Energy and Material Demand Modelling and Scenarios, submitted to ARER

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Evaluation of the impact of low carbon lifestyles on quality of life

Final version report 2024

Contribution from the University of Groningen, the Netherlands to EDITS (Energy Demand changes Induced by Technological and Social innovations) Project

by Anne M. van Valkengoed[1*] & Linda Steg[1]

Submitted to

Research Institute of Innovative Technology for the Earth (RITE), Japan

and

the Ministry of Economy, Trade and Industry (METI), Japan

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1. Introduction

To achieve rapid reductions in CO_2 emissions, change across all sectors of society is necessary (IPCC, 2023). So far, climate models have mostly focused on how reductions in CO_2 emissions can be achieved by supply-side solutions, which are often technological solutions that make the supply of energy more sustainable (IPCC, 2022). It is however becoming apparent that supply-side solutions alone are likely not sufficient to achieve rapid reductions in CO_2 emissions, and that demand-side changes are also necessary (e.g., Grübler et al., 2018). Demand-side solutions are solutions that reduce the demand for energy, goods, and services, and involve for example changes in lifestyle and more efficient use of resources (Grübler et al., 2018).

While the potential of demand-side solutions, and especially lifestyle changes, in reducing CO_2 emissions is promising (e.g., van den Berg et al., 2019), there are concerns that people's well-being and quality of life may be negatively affected by these changes. For example, smaller living spaces and more shared spaces represents an important step towards more sustainable lifestyles (e.g., Sandberg, 2021), but could thwart people's need for privacy. A recent study however inventoried the potential effects of demand-side solutions on well-being, and found that across the board, demand-side solutions are compatible with high levels of well-being (Creutzig et al., 2021). Importantly, this study specifically focused on examining how demand-side solutions are associated with objective indicators that determine well-being, such as air quality, access to sufficient and safe food, and exposure to crime (Creutzig et al., 2021).

In addition to such objective indicators of well-being, people also hold a subjective evaluation of their well-being (e.g., Ryan & Deci, 2001; Oswald & Wu, 2010). So far, studies have not yet systematically examined how people's subjective well-being relates to demand-side solutions. Yet, studying how subjective well-being is affected by demand-side solutions is critical for two reasons. First, people's subjective evaluations of their own well-being are often correlated with objective indicators, but do not completely overlap (e.g., Oswald & Wu, 2010). People's subjective perceptions of their own well-being thus hold information that is not accounted for fully by objective indicators - subjective evaluations typically matter more.

Second, people's expectation of how their well-being is affected by lifestyle changes may not necessarily align with their actual experience. For example, studies have found that people often oppose environmental policies strongly before they are implemented, but are more positive in their evaluation after the policy has been in place for some time (van Wee et al., 2023). Critically, the anticipation of a decrease in well-being can result in resistance and a lack of support for sustainable policies, reducing the political mandate necessary to implement them (e.g., Vonk Noordgraaf et al., 2014; Bergquist et al., 2022; Anderson et al., 2017). Understanding when and why people anticipate that their well-being will be negatively affected is thus critical to ensure policies are designed and introduced in such a way that they engender the least amount of resistance and can be implemented successfully.

In this study, we therefore aim to examine how people evaluate a scenario that showcases what life looks like in the future where many demand-side changes are implemented. We specifically assess how people expect their quality of life will change under this scenario, and how this in turn relates to their acceptability of the scenario.

Quality of life is a concept that is closely related to the concept of well-being, and is used among others by the WHO to examine how people evaluate their position in life (Skevington & Böhnke, 2018). Quality of life research specifically assesses how people evaluate different important domains that together make up people's overall life experience, such as people's health, social connections, and environmental quality in their place of residence (e.g., WHO, 2012). This approach thus gives a specific insight into which domains people expect demand-side solutions or lifestyle changes to enhance or reduce their quality of life. In addition, quality of life measures can be used to assess which domains people find most important in life (see Poortinga et al., 2004). This approach can thus help us to understand

better when and why people find demand-side changes more or less acceptable. Specifically, we expect that people will find the scenario less acceptable if they perceive that it negatively affects those quality of life domains that people find most important.

1.2. Methods

1.2.1. Participants and procedure

Participants for this study were collected via three different approaches. First, 235 first-year psychology students were recruited for participation via SONA, a student participants pool of the University of Groningen. These students completed the questionnaire online and received course credits as compensation for their time. Second, 199 students from the faculty of economics and business completed the questionnaire as part of a series of studies that were completed in the lab on location. Participants received €10 for their participation in the study. Lastly, 250 members of the Dutch general public participated in the study via Prolific.co. Participants completed the survey online and received £2 for participating. The part of the study conducted with students was exempted from ethical review by the ethics committee of the University of Groningen, as it is a low-risk study. The part of the study conducted via Prolific.co was reviewed and approved by the ethics committee of the University of Groningen. We discuss the findings of the 3 participants groups simultaneously (total n = 681, after removing incomplete responses and failed attention check, see below).

The study was completed digitally in Qualtrics and could be completed in Dutch or English. Participants first read an informed consent form and indicated their consent to participate. Next, participants were asked to indicate their current level of life satisfaction, and to indicate how important they find 15 different quality of life domains for their own well-being. Participants then watched a video (length 2:41) produced by the Dutch Youth Climate Movement. The video features an animation and narrated voice-over (in Dutch, English subtitles were provided) that describes life in the Netherlands in the year 2040. This video showcases a scenario that introduces many demand-side solutions to climate change, including working fewer hours, circular economy, purchasing fewer items, car-free cities, smaller homes, sharing economy, shifts to a plant-based diet, and flying less. Participants then completed an attention check to ensure they saw the video (4 participants were removed for failing the attention check). Next, participants indicated how acceptable they find the scenario, how acceptable they think others find the scenario on average, and how feasible they find the scenario. Then participants evaluated how they expect their quality of life to change if the scenario was implemented. The order of these blocks of items was counterbalanced: people randomly either completed the acceptability items or the quality of life items first. The survey ended with questions assessing people's climate change perceptions and demographic information. In this report, we specifically focus on how people think the scenario will affect their quality of life, and how acceptable they find the scenario.

1.2.1. Measures

Quality of life - importance. Participants were presented with a list of 15 quality of life domains including a label and a description (see Table 1). Participants indicated how important they find each domain to their overall quality of life using a 5-point Likert scale ranging from 1 (not at all important) to 5 (very important). The 15 quality of life domains were adapted from Poortinga et al. (2004), who present a list of 22 domains. To ensure the domains were relevant for this study and to keep the questionnaire as brief as possible, we selected from and adjusted the domains provided by Poortinga et al. (2004) as follows. We adopted the following 12 domains without alteration or with only minor adjustments to the description in order to improve comprehension among our participations: health, comfort, environmental quality, freedom, identity and self-respect, free time, money and income,

nature and biodiversity, social relations, privacy, safety, social justice. We combined challenge/excitement and change/variation into one domain we label Fun ('doing fun and varied activities in daily life'). We combine work and education into one item we label Work and Education ('The possibility to find or perform work or education that fits well with your interests and skills.). We excluded the following 6 domains as they were already addressed in other domains or not directly relevant to the demand-side solutions depicted in the scenario: aesthetic beauty, material beauty, partner and family, security, spirituality/religion, and status/recognition. Lastly, we added one final domain to our list that covers the quality of the living environment ('An aesthetically pleasing and nice living environment.').

Quality of life - expected changes. After watching the video showcasing the scenario, participants were asked to respond on a 7-point Likert scale to the following question: If I would live my life as described in the video, my quality of life would ... become much worse (1), become moderately worse (2), become a little bit worse (3), stay the same (4), become a little bit better (5), become moderately better (6), become much better (7). Then, for the same 15 quality of life domains as mentioned above (see Table 1), participants indicate how they expect each domain to change if they would live their life as presented in the scenario. Perceived changes in quality of life were assessed with a 7-point Likert scale (1 = become much worse, 4 = stay the same, 7 = become much better).

Acceptability. Acceptability of the scenario was assessed using the following four items: I think the lifestyle presented in this video is … totally unacceptable (1) – very acceptable (7), not good at all (1) - very good (7), very negative (1) – very positive (7), not at all necessary (1) – very necessary (7) (based on Liu et al., 2019). Responses across the four items were averaged to create an overall scale for acceptability (M = 5.70 SD = 1.29, α = .94).

Table 1
Quality of life domains assessed in this study

Label	*Description*
Health	Good physical and mental health. Having access to healthcare
Living environment	An aesthetically pleasing and nice living environment.
Fun	Doing fun and varied activities in daily life
Comfort	Having a comfortable and easy daily life.
Work and education	The possibility to find or perform work or education that fits well with your interests and skills.
Environmental quality	Living in an environment with clean water, clean air, and no ground pollution. No or minimal exposure to harmful substances in daily life.
Freedom	Freedom and control over the course of one's life, to be able to decide for yourself, what you do, when, and how

Identity and self-respect	Having sufficient self-respect and being able to develop one's own identity.
Free time	Having enough time off to do things after work and other responsibilities
Money and income	Having enough money to buy and to do the things that are necessary and pleasing.
Nature and biodiversity	Assurance of the continued existence of plants and animals, maintaining biodiversity. Being able to enjoy natural landscapes, parks, and forests.
Social relations	Having good social relations with family, friends, colleagues, and neighbors. Being able to maintain these contacts and make new ones.
Privacy	Having the opportunity to have a place of your own, to do your own things
Safety	Being safe in and outside the home
Social justice	Having equal opportunities and having the same possibilities and rights as others. Being treated in a righteous way.

1.3. Results

1.3.1. Importance of quality of life domains

Across the board, all quality of life domains were on average rated as at least somewhat important. On average, people found health (M = 4.70), safety (M = 4.56), and freedom (M = 4.36) the most important quality of life domains for their own well-being. People found nature and biodiversity (M = 3.73), comfort (M = 3.84), and living environment (M = 3.99) the least important quality of life domains. An overview of the average importance of each domain is presented in Figure 1.

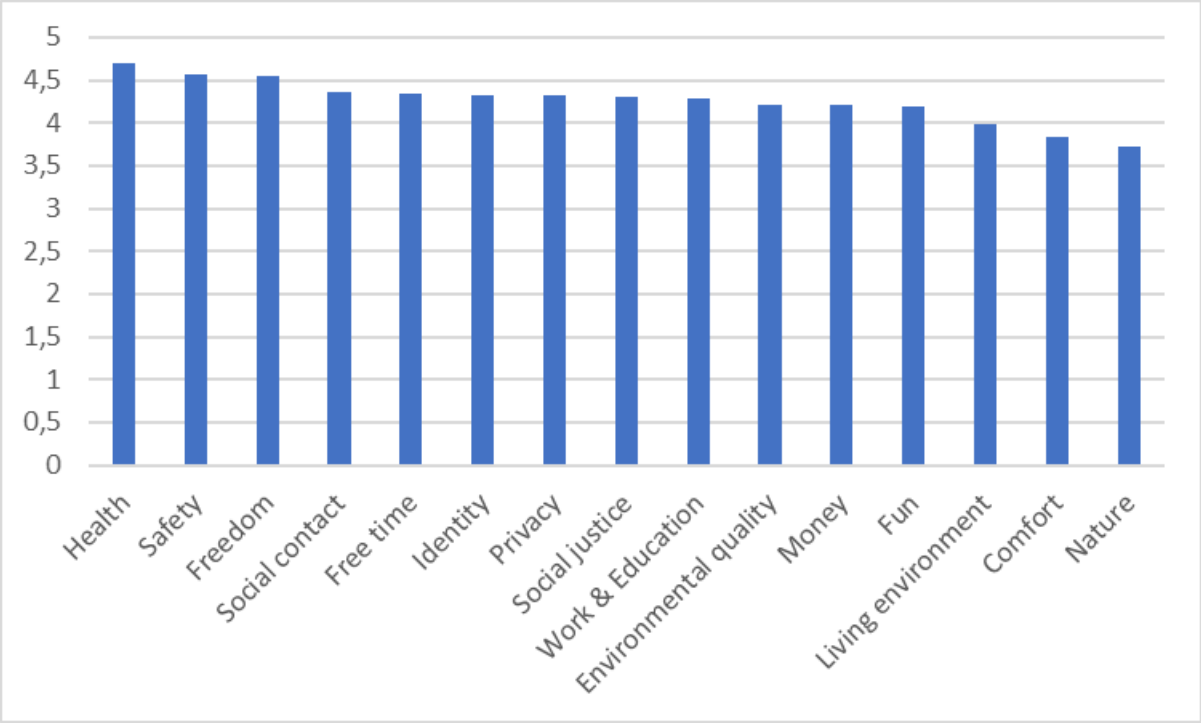

Figure 1. An overview of how important on average respondents found each quality of life domain for their own well-being on a scale from 1 (not important at all) to 5 (very important).

1.3.2. How is quality of life perceived to be impacted by the scenario?

Overall, most people expect that their quality of life would increase if they lived their life as described in the scenario: a total of 72% of respondents indicate their quality of life would be better under the scenario, 11.4% indicates their quality of life would stay the same, while 16.7% expect their quality of life to decrease under the scenario.

We next examine how people expect each of the individual quality of life domains to change (see Figure 3). On average, people expect that the following domains will become better (M > 5): nature and biodiversity (M = 6.45), environmental quality (M = 6.42), living environment (M = 5.88), health (M = 5.45), and free time (M = 5.12). People expect no changes in the domains of fun (M = 4.54), comfort (M = 4.47), work and education (M = 4.49), identity and self-respect (M = 4.43), social connections (M = 4.78), safety (4.75), and social justice. People expect the following domains will become slightly worse (M < 4): money and income (M = 3.80), privacy (M = 3.92), and freedom (M = 3.95).

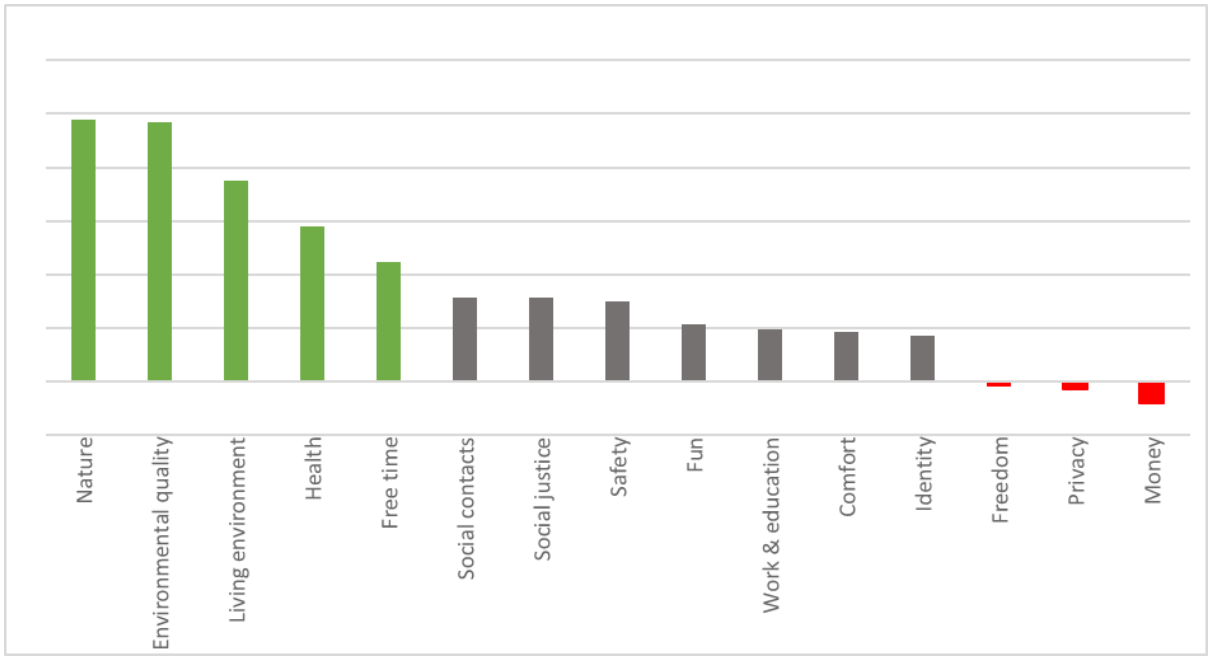

Figure 2. An overview of how participants expect the Quality of Life domains would be positively (green), negatively (red), or not (gray) affected if they would live their life as presented in the scenario.

1.3.3. Acceptability of the scenario

On average, most people found the scenario highly acceptable, with the acceptability of the scenario rated an average of 5.7 on a 7-point scale. A total of 81% of participants found the scenario acceptable, 9% had a neutral evaluation of the scenario, and 10% found the scenario unacceptable. To better understand why people do or do not find the scenario acceptable, we examine differences between people who rated the scenario as unacceptable (acceptability < 4, n = 68) and participants who rated the scenario as acceptable (acceptability > 4, n = 552). Specifically, we examine which quality of life domains these participants find most important, and which domains they think will be most changed under the scenario.

Figure 3 and Figure 4 present an overview of how important each group found each quality of life domain, and which changes they expect to happen to the quality of life domains under the scenarios. Interestingly, both groups found health, freedom, and safety the most important domains. The group that found the scenario unacceptable expected the domains freedom, money and income, privacy, fun, and identity to worsen under the scenario. An especially big decrease in quality of life was expected in the domain of freedom, which is also a domain which this group found highly important. They also expect an increase in the domains of nature and biodiversity and environmental quality, but these are both domains which are relatively unimportant to this group.

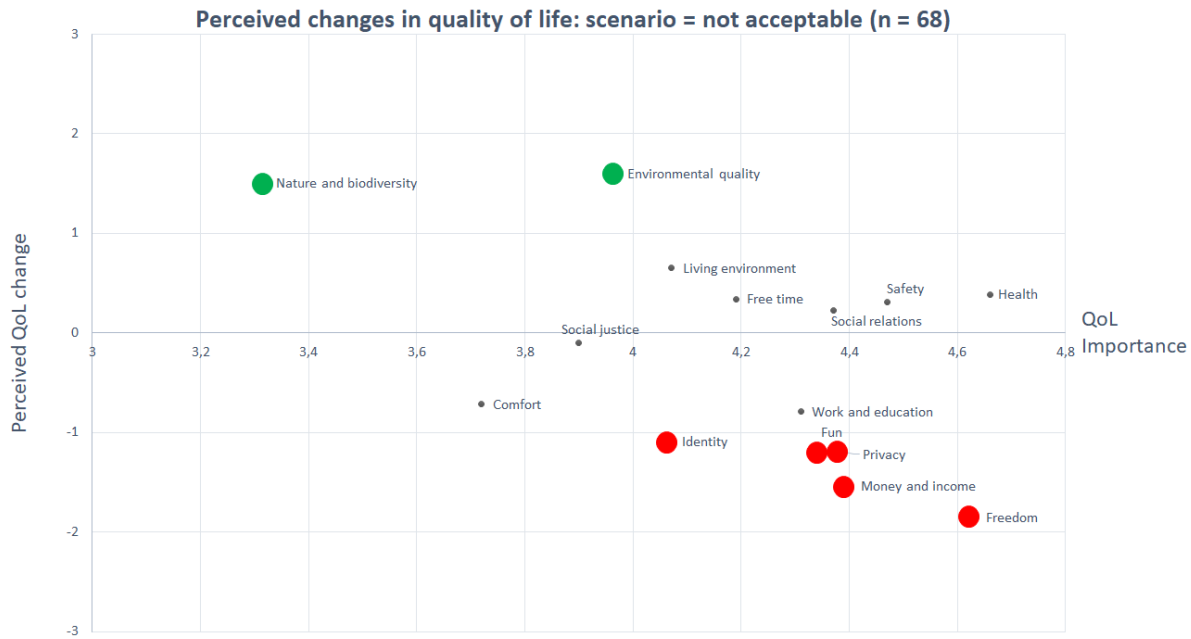

Figure 3. Overview of how important participants who did not find the scenario acceptable find different quality of life domains (x axis) and which quality of life domains they expect to improve (green) and worsen (red) under the scenario (y axis).

Figure 4. Overview of how important participants who found the scenario acceptable find different quality of life domains (x axis) and which quality of life domains they expect to improve (green) and worsen (red) under the scenario (y axis).

The group who found the scenario acceptable did not expect there would be any negative impacts to the quality of life domains, a notable difference with the group who found the scenario unacceptable. They also perceived an increase in the domains of health, free time, environmental quality, living environment and nature and sustainability. Another important difference between the groups lies in the perceptions of the quality of life domain of health, which was the most highly valued out of all domains. The participants who evaluated the

scenario as acceptable expected an increase in the domain of health, whereas the participants who evaluated the scenario as unacceptable did not think the domain of health would change.

1.4. Discussion

Demand-side solutions represent an important strategy to reduce CO_2 emissions and are compatible with high-levels of well-being. Yet, current investigations of demand-side policies have focused on objective indicators of well-being, and it is therefore not clear how people subjectively evaluate demand-side policies. Yet, if people perceive demand-side solutions as worsening their quality of life, this could lead to resistance, which lowers the political mandate needed to implement demand-side policies. It is therefore important to know how people perceive demand-side solutions and why people find such policies (not) acceptable.

In this study, we presented a video to people showcasing a scenario that introduced a variety of demand-side policies, and asked for their opinions on how they expect this scenario would affect their quality of life, as well as how acceptable they found the scenario. Our findings offer a first systematic examination of how people respond to a scenario where demand-side solutions are introduced, yielding two critical main insights.

First, we found that the scenario in our study was evaluated very positively. The vast majority of respondents (72%) expected that their quality of life would increase under the scenario, which is in line with scientific assessments that have found that demand-side solutions are compatible with high levels of well-being. Even more participants (81% of respondents) rated the scenario as acceptable, which indicates they find the scenario good, necessary, useful and acceptable. As the scenario used in the study bears close resemblance to the EDITS LED and High with Low scenarios, this gives a first indication that people may in general perceive such scenarios based on demand-side solutions as a desirable solution to climate change, and that the political mandate to implement such policies may be higher than expected. In general, these findings track with recent studies that have found that support for climate policies is generally high across the globe, and that there is a tendency to underestimate the support for climate policies (see for example Andre, Boneva, Chopra, & Falk, 2024).

Second, our findings also shed light on why people do not find the scenario acceptable. While this group represents a minority in the current study, previous research has found that particularly opponents of a policy or measure are motivated to voice their opposition or protest the implementation of a measure (e.g. Liu, Perlaviciute & Squintani, 2022). This minority group may thus be particularly vocal and powerful in expressing resistance to demand-side solutions, which may make it seem that the political mandate for implementing policies is much lower than it is in practice. Our results indicate that people who did not find the scenario acceptable still had a relatively nuanced evaluation of its impacts. For example, they did expect that the domains of environmental quality and nature and biodiversity would increase under the scenario. However, they particularly anticipated a decrease in highly-valued quality of life domains, which include freedom, money and income, and privacy. These findings indicate that any communication surrounding demand-side solutions, particularly those aimed at including opponents of these policies in the conversation, should take into consideration that this group feels that very important quality of life domains are threatened, and they will therefore likely feel strong emotions and concern about the scenario. Based on our findings, communicators can develop strategies that accurately acknowledge these concerns, and find possible ways to address them.

We will further advance this line of research in two ways. In the short-term, we are currently preparing a cross-cultural replication of this study in collaboration with EDITS-member Prof.

Dr. Masahiro Sugiyama. The cross-cultural replication will specifically take place in Japan and India, and will aim to examine the extent to which the findings of our initial study are generalizable to other cultural contexts. Once the data collection for the cross-cultural replication has been completed, we will write up the joint results of this work for a journal article.

Second, we will use the basic methodology we have developed here in the new EDITS fast-track programme 'WELL-with-LOW - Wellbeing Metrics and Assessment of LED-type Policy Options". Specifically, this fast-track will consist of the development of a tool that allows users to examine the influence of supply- and demand-side policies on CO_2 reductions as well as on objective indicators of well-being. We will use the methodology introduced here to examine people's responses to this tool, specifically examining when and why people prefer supply- or demand-side policies, what impacts they expect these policies to have on their quality of life, and to examine which information should be presented (and how) in order to achieve support (or lower resistance) to demand-side policies.

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2023 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 へ参加し，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） 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．

3） 日本を対象に開発してきた家庭部門エネルギー最終需要モデルを海外のストックに適用した．

本報告書では，3)の内容を報告する．２節では検討の概要を説明する．３節，４節ではエネルギー需要推計の基礎データである気象データ，人口・世帯構成に関するデータを整備した結果を報告する．５節では新規に開発したセントラル暖房システムの計算モジュールについて説明する．６節に成果をまとめ，今後の課題を示す．

2. 家庭部門エネルギー最終需要モデルの海外ストックへの適用

Low energy demand（LED）シナリオ[1)]は，ネガティブエミッション技術に頼ることなく 1.5℃の地球温暖化の目標達成が可能であることを示した．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の要素について LED シナリオが示すような変化を想定し，その効果を定量化してその意義を示すことが重要である．一方で，これまで推計に広く用いられているモデルでは，住宅・建築物の床面積当たり原単位を用いてエネルギー需要を推計する方法など，簡易な方法が採用されてきた．この結果，対策導入効果に関する条件依存性や対策間の相互作用が無視されて推計誤差が大きくなる，多様な対策を考慮することができないなど，分析上の課題が生じうる．これに対して，近年建築工学分野では個々のエネルギー消費を積み上げてシミュレーションベースでエネルギー需要を推計する方法が開発されており，技術普及によりもたらされる二酸化炭素排出量削減ポテンシャルの評価に使用されるようになった．LED シナリオが描く行動変容などを積み上げ型エネルギー需要モデルで考慮する

ことができれば，上記の問題を解決することが可能であると考えられるものの，現時点ではそのような取り組みは行われていない．このような背景から，日本の家庭部門を対象として開発してきた積み上げ型エネルギー需要モデルの一つである大阪大学下田研究室の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）を海外のストックに適用することを計画している．今年度はこの準備段階として，データ整備と新規のモジュール開発を行った．

2.1. TREES モデルの概要

2020 年度の報告書において TREES モデルの詳細を説明しているため，本節では概要のみを説明する．図 1 に推計手順の概要を示す．日本の住宅ストックに適用する場合，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．

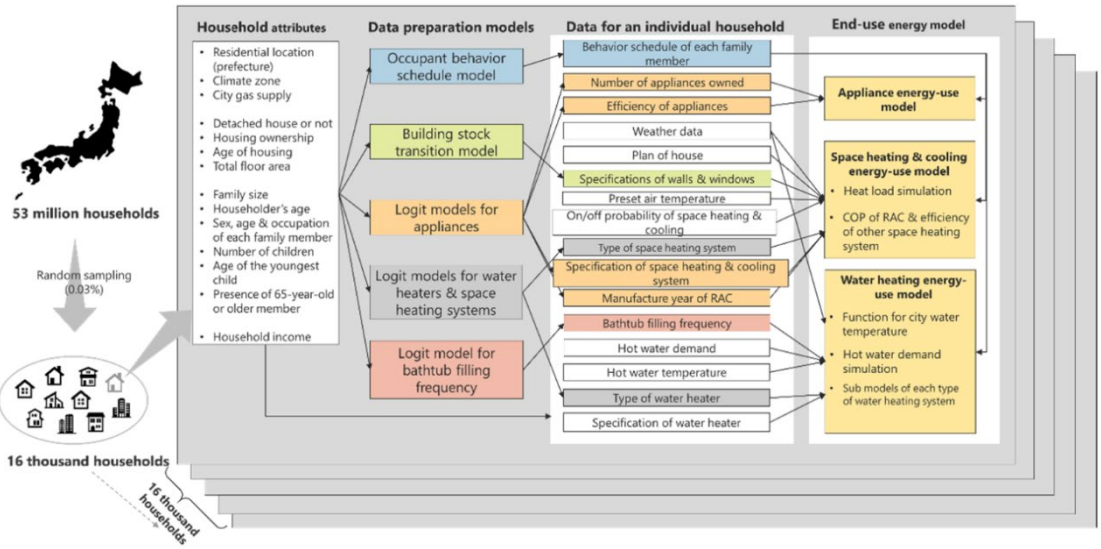


図 1　TREES モデルの概要

次に，これらの条件の下で，１年間 5 分タイムステップで代表世帯のエネルギー需要を推計する．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．次に，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．最後に，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，集合住宅・戸建住宅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．

3. TREES への典型気象データの適用

TREES モデルでは入力条件の一つとして気象データを用いている．世界版 TREES の実現に向け，利用可能な気象データを調査し，TREES モデルへの適用可能性を検討した．調査の結果得られた気象データを用いて TREES によるエネルギー消費量シミュレーションを行い，これまでに研究室で用いてきた気象データによる推計結果と比較し，利用可能な気象データの妥当性を評価する．

3.1. 利用可能な気象データ

調査の結果，EnergyPlus[3]や Climate.OneBuilding.Org[4]などから「epw」形式のファイル（EPW ファイル）の典型気象データが提供されていることがわかった．EPW (EnergyPlus Weather File) ファイルは，建築物のエネルギー消費量の計算において広く利用されている EnergyPlus が定める形式に従った気象データである．EPW ファイルには外気温度や相対湿度，全天日射量，雲量など，建築物のエネルギー消費量の推計に必要な気象データが 1 時間単位で格納されている[5]．また，典型気象データとは，各月について，気温や日射量，相対湿度などの統計値（最大値，最小値，平均値など）を参照して複数年の気象データから最も典型的なものを選択し，それらを組み合わせて一年分のデータとしたものである．これは建築設備のシミュレーション分野において広く用いられている．

Climate.OneBuilding.org は全世界 16,100 地点以上について典型気象データを提供している．Climate.OneBuilding.org のデータソースは NCEI(National Centers for Environmental Information) の ISD（Integrated Surface Database）[6]と ECMWF（European Centre for Medium-Range Weather Forecasts）の ERA5（ECMWF Reanalysis v5）[7]である．このサイトより典型気象データ（TMYx: Typical Meteorological Year x）を取得し，時間粒度やデータ構造を変換することで TREES に適用できるようにした．

TREES モデルは日本で利用可能な 1 分タイムステップの気象データを用いているため，フォーマットの変更とデータの内挿を行った．瞬時値である気温や気圧については，各 1 時間値を前後 30 分間に格納して一分値とした．一方，量的なものである日射量や降水量については，各時間の値を 60 で割り，それを直前 60 分間に格納した．この理由は，気象庁のデータ統計で 1 時間単位の日射量と降水量が前 1 時

間の合計値として公表されており[8]，また，通常の EPW ファイルでは日射量が前 1 時間の合計値となっている[9]ためである．降水量については明確な根拠がないが，同じ量的なデータである日射量と同様の処理を行うことが適切だと考えた．しかし，EPW ファイルの作成方法・データソースによっては量的なデータも瞬時値データと同様に扱うことが適切な可能性がある．より適切な処理のためには，データソースの確認と，統計処理の方法が明らかなデータ（例えば気象庁のデータ）と比較したうえで，その妥当性を検討することが必要である．

3.2. 検証

検証にあたって，Climate.OneBuilding.org から取得した大阪の典型気象データを用いて TREES モデルによる大阪住宅ストックのエネルギー需要推計を行い，その結果を同地域の 2013 年から 2021 年の気象データを用いて得られた推計結果と比較した．年間値，月推移，日推移，時間推移についてそれぞれ比較することで，加工した典型気象データを用いても問題なく推計が行えることを確認する．なお，使用した大阪の典型気象データ（TMYx）では，1 月に 2021 年（2020 年度），2 月に 2015 年（2014 年度），3 月に 2016 年（2015 年度），4 月に 2009 年，5 月に 2008 年，6 月に 2010 年，7 月に 2011 年，8 月に 2011 年，9 月に 2008 年，10 月に 2014 年，11 月に 2016 年，12 月に 2009 年のデータが格納されている．2013 年度以降のもの（1 月，2 月，3 月，10 月，11 月）についてはそれぞれ観測気象データと対応している．2007 年度から 2012 年度については気象観測データを保有していないため，典型気象データの作成における対象期間全てに推計結果が示されているわけではないことに注意されたい．

（1）年間値

図 2 から図 11 は，2013 年度から 2021 年度の気象データを用いた場合（青棒）と典型気象データを用いた場合（赤破線）の年間エネルギー消費量推計値（ストック積算値）をエネルギー種別，用途別で示す．図 2 から図 5 は暖冷房用途，図 6 から図 8 は給湯用途，図 9 から図 11 は総量を表す．いずれも赤い点線で典型気象データを用いた場合に得られた推計結果を示しており，全てのエネルギー種・用途の推計結果において典型気象データを用いて得られた推計値が 2013 年から 2021 年の気象データを使用して得られた推計値のおおむね中間に位置していることが確認された．この結果は典型気象データが典型的な気象データとしての代表性を有することを示唆するものである．

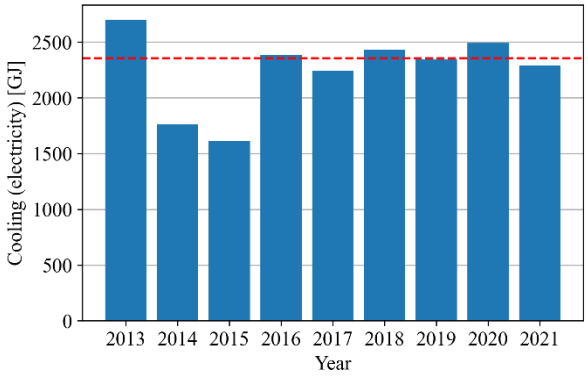


図 2　冷房による年間電力消費量

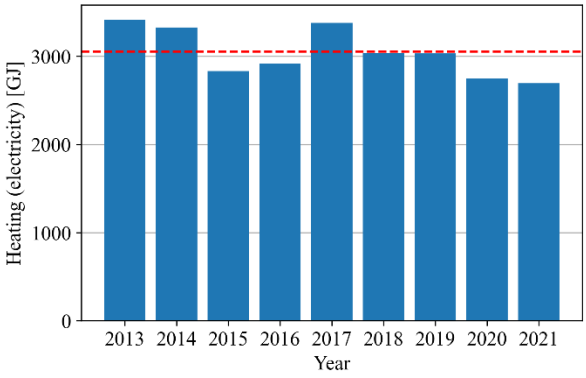


図 3　暖房による年間電力消費量

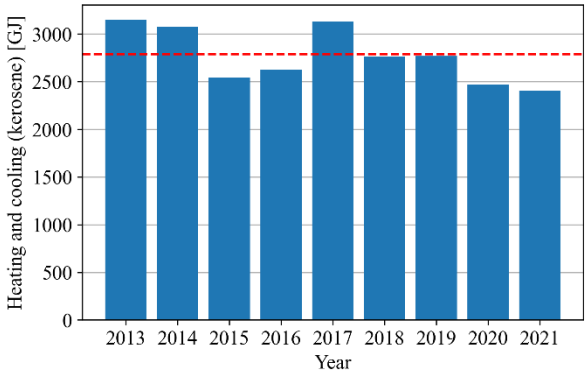


図 4　暖冷房による年間灯油消費量

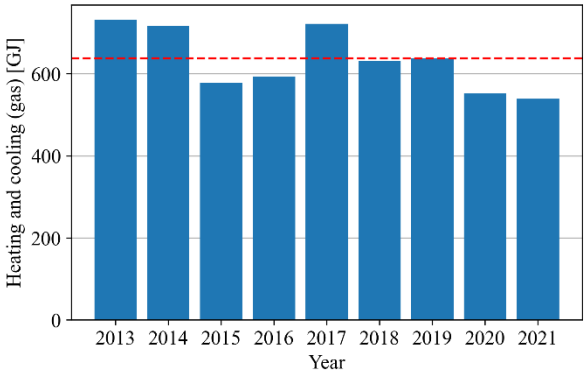


図 5　暖冷房による年間ガス消費量

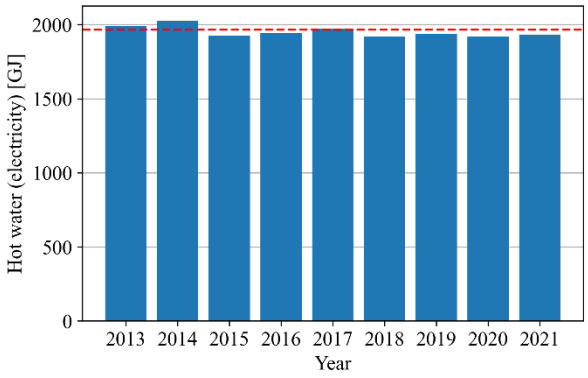


図 6　給湯による年間電力消費量

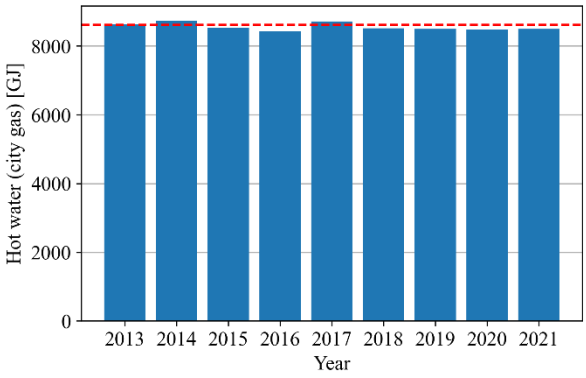


図 7　給湯による年間都市ガス消費量

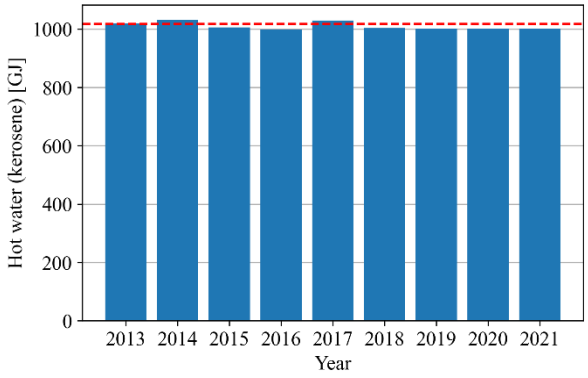


図 8　給湯による年間灯油消費量

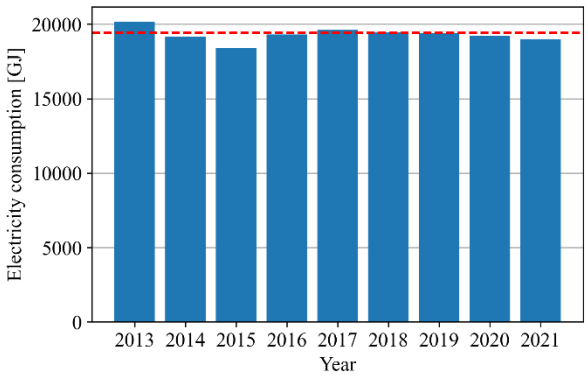


図 9　年間電力消費量

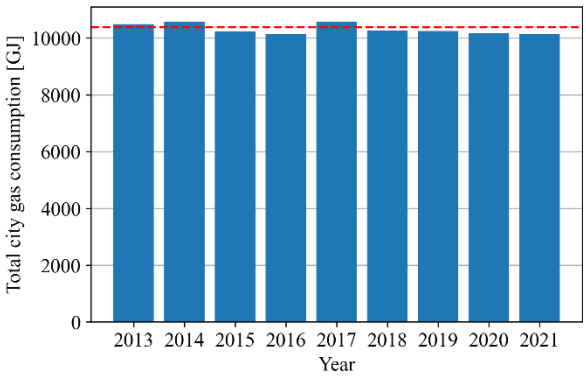


図 10　年間都市ガス消費量

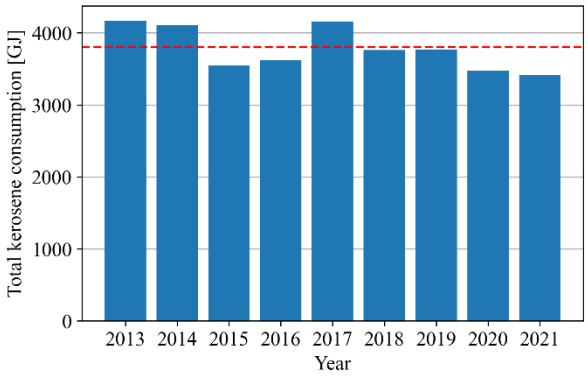


図 11　年間灯油消費量

（2）月推移

図　12 から図　21 は，2013 年度から 2021 年度の気象データを用いた場合と典型気象データを用いた場合のエネルギー消費量推計値を月別，エネルギー種別，用途別で示したものである．それぞれ異なる色が異なる年度の気象データを用いた結果を示しており，凡例において 9999 は典型気象データを用いた場合を表している．典型気象データを用いた場合，どのエネルギー種・用途に関しても概ね全体の中

央値程度を示しており，月単位でも「典型的な」推計結果となっているといえる．

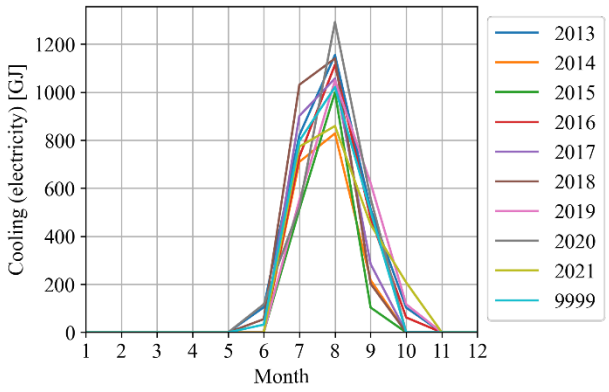


図 12　冷房：月別電力消費量

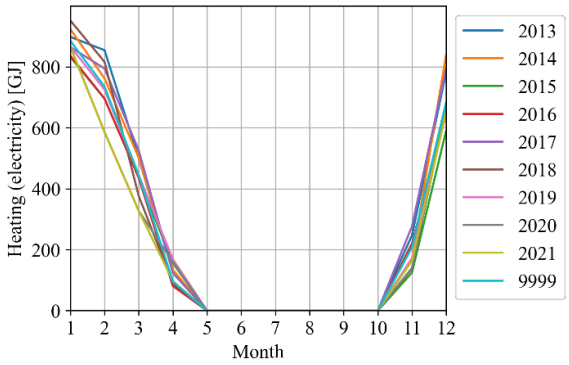


図 13　暖房：月別電力消費量

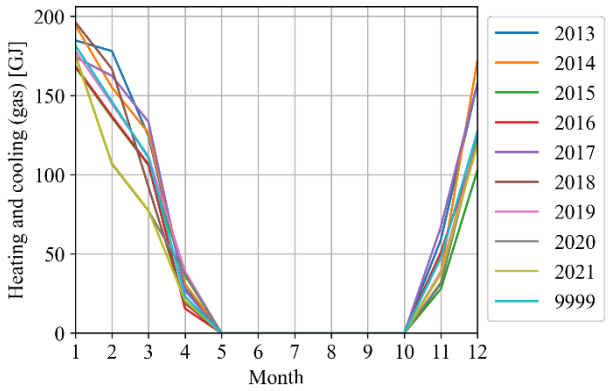


図 14　暖冷房：月別灯油消費量

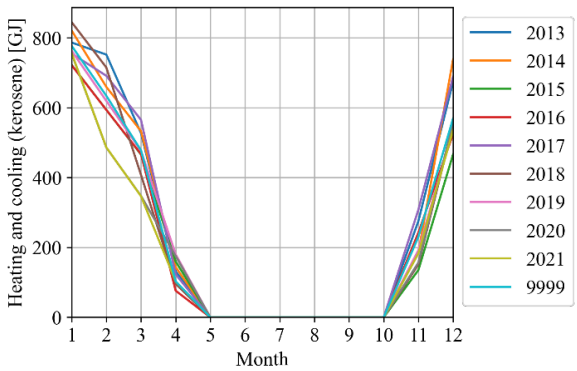


図 15　暖冷房：月別ガス消費量

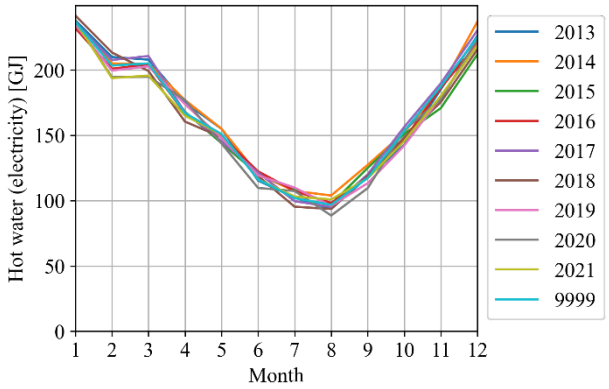


図 16　給湯：月別電力消費量

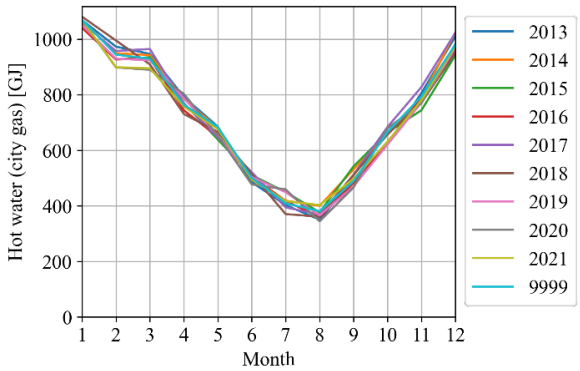


図 17　給湯：月別都市ガス消費量

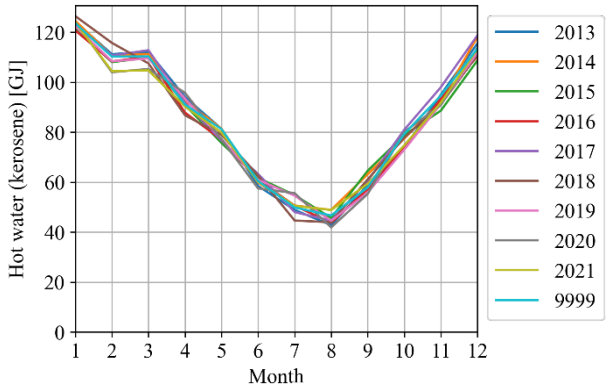


図 18　給湯：月別灯油消費量

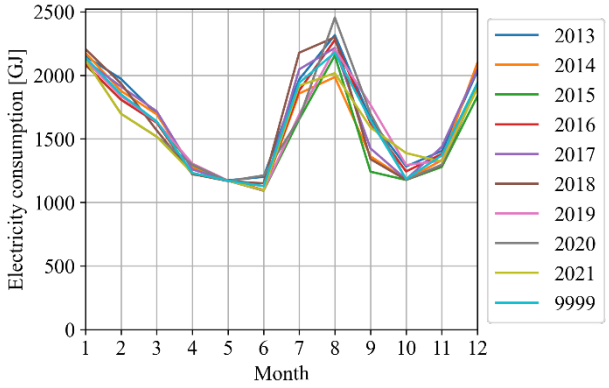


図 19　月別電力消費量

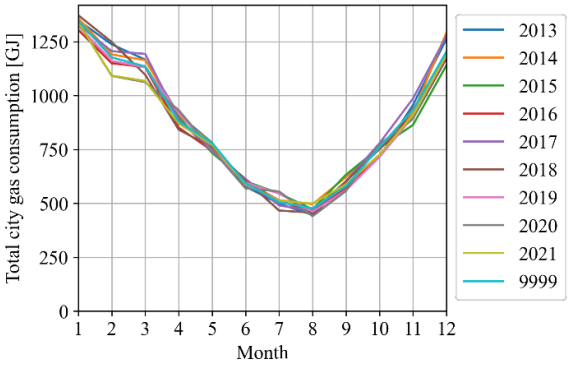


図 20　月別都市ガス消費量

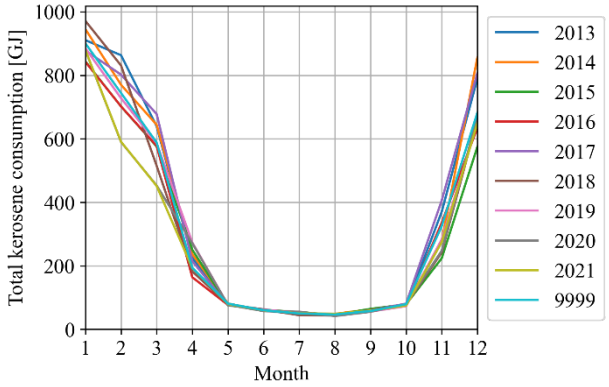


図 21　月別灯油消費量

（3）日推移

前述の通り，使用した典型気象データでは，各月について，複数年の気象データから最も典型的なものを選択し，合わせて一年分のデータとしている．そのため，月単位では，典型気象データを用いた場合と観測気象データを用いた場合とで，同じ期間についてのデータによるシミュレーションを行うことができる．代表的な結果として，図 22 と図 23 に 2 月の日別電力消費量と 11 月の日別都市ガス消費量

を示す．典型気象データにおいて，2 月は 2014 年度，11 月は 2016 年度の気象データを格納している．典型気象データを使った場合のエネルギー消費量は，対応する年の推計結果と概ね同様の推移となっていることが読み取れる．

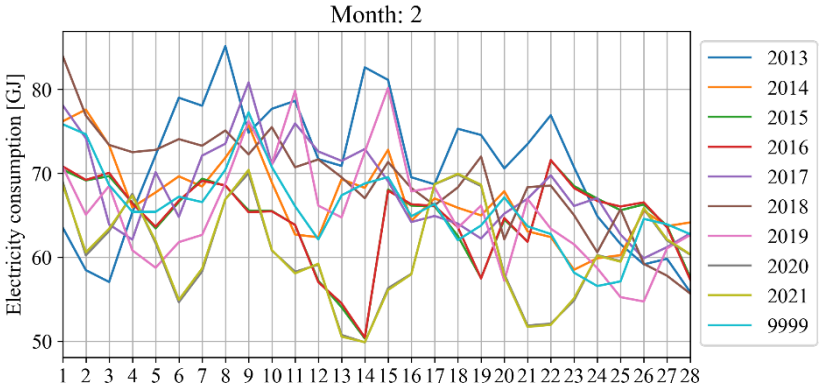


図 22　2 月（2014 年度に対応）の日別電力消費量

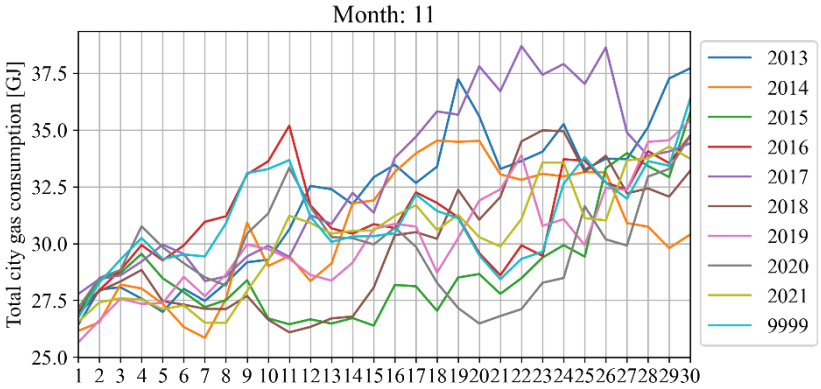


図 23　11 月（2016 年度に対応）の日別都市ガス消費量

（4）時間推移

代表的な結果として，図 24 と図 25 に 2 月 10 日の日別電力消費量と 11 月 10 日の日別都市ガス消費量を示す．これらの図のように，典型気象データを使った場合，対応している年の推計結果と同様の推移を示すことが多い．ある程度の差異が生じることはあるが，対応する年の推計値から大きく外れることはほとんどなく，典型気象データを使用して「典型的な」結果を算出する上で，1 時間単位でも大きな問題はないといえる．

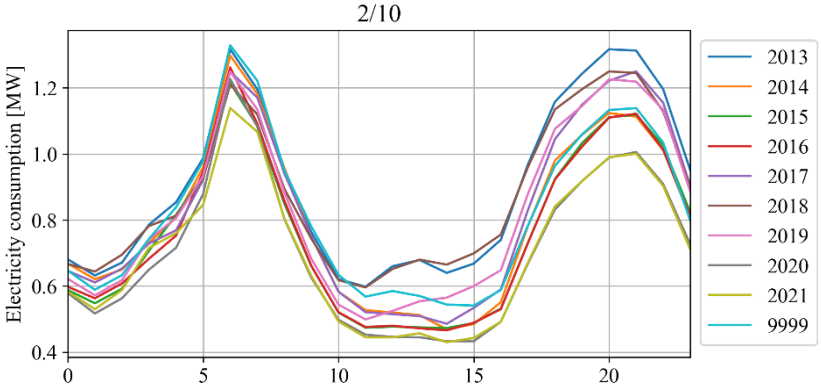


図 24　2 月 10 日（2014 年度に対応）の時間別電力消費量

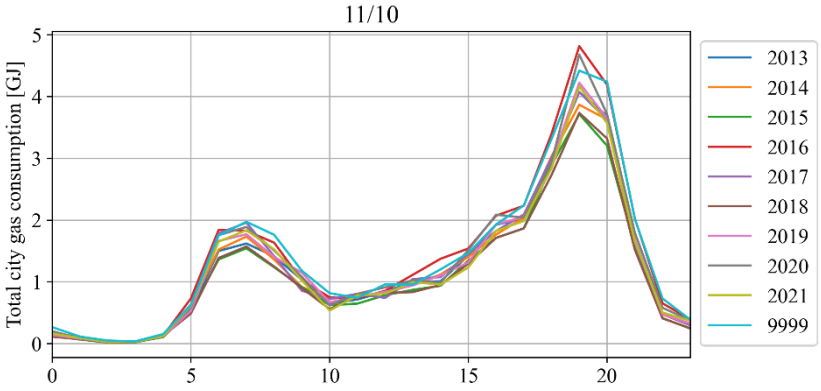


図 25　11 月 10 日（2016 年度に対応）の時間別都市ガス消費量

3.3.　本節のまとめ

Climate.OneBuilding.org では世界の代表的都市における典型気象データを配布している．大阪の観測気象データと典型気象データを用いて TREES で住宅ストックエネルギー需要推計を行い，その結果を比較したところ，典型気象データを用いて得られた推計結果は，2013 年から 2021 年の観測気象データを用いて得られた推計結果の中間に位置することがわかった．また，日別値と時間別値については観測データと同様の値・推移を確認することができた．この結果から，典型気象データを用いて得られた推計結果は典型的なエネルギー需要の推計値であると評価することができ，TREES 世界版において典型気象データを用いることは問題ないと考えられる．

4.　世帯情報・住宅情報の整備

TREES モデルの日本版では国勢調査及び住宅土地統計調査に基づいて，表 1 に示す世帯属性や住宅の仕様を有する代表世帯を生成する．TREES モデルの海外ストックへの適用においても同様の人口・世帯のモデリングが必要となる．そこで，人口・世帯数・住宅仕様に関する統計資料を調査し，利用可能な統計資料を用いて世帯情報・住宅情報の整備が可能か検討した．本節は，各国の統計資料の調査結果と，

世帯情報・住宅情報の整備手法について報告する.

表 1　推定項目及び分類

項目		分類
世帯属性	年齢	0～104 歳
	性別	男，女
	就業・就学形態	フルタイム，パートタイム，小学生，中学生， 高校生，短大・専門学校・大学・大学院生，その他
	職業	管理的職業従事者，専門的・技術的職業従事者，事務従事者， 販売従事者，サービス職業従事者，保安職業従事者， 農林漁業従事者，生産工程従事者，輸送・機械運転従事者， 建設・採掘従事者，運搬・清掃・包装等従事者， 分類不能の職業
	世帯人数	1 人，2 人，3 人，4 人，5 人，6 人以上
住宅の仕様	所有形態	持ち家，公営・都市再生機構・公社の借家， 民営の借家，給与住宅
	延床面積	0～19m2，20～39m2，40～59m2，60～79m2，80～99m2，100～119m2，120～149m2，150～199m2，200m2～
	建て方	集合住宅，戸建て住宅
	TREES モデルにおける住宅類型	集合 1～集合 6，戸建て 1～戸建て 6

4.1. 統計資料の調査

(1)　人口

国連が発行する World Population Prospects 2022[10)]から，236 の国と地域の 1950 年から 2100 年にかけての人口の推計値を得ることができる.

(2)　世帯数

国連統計局が発行する Demographic Year Book[11)]から，123 の国と地域の世帯人数別世帯数を得ることができる．図 26 に本資料の一部を示す．この資料は各国で実施された人口センサスのデータに基づいて作成されているため，データが得られない国が多く，得られても調査年が国よってばらばらである点に注意が必要である.

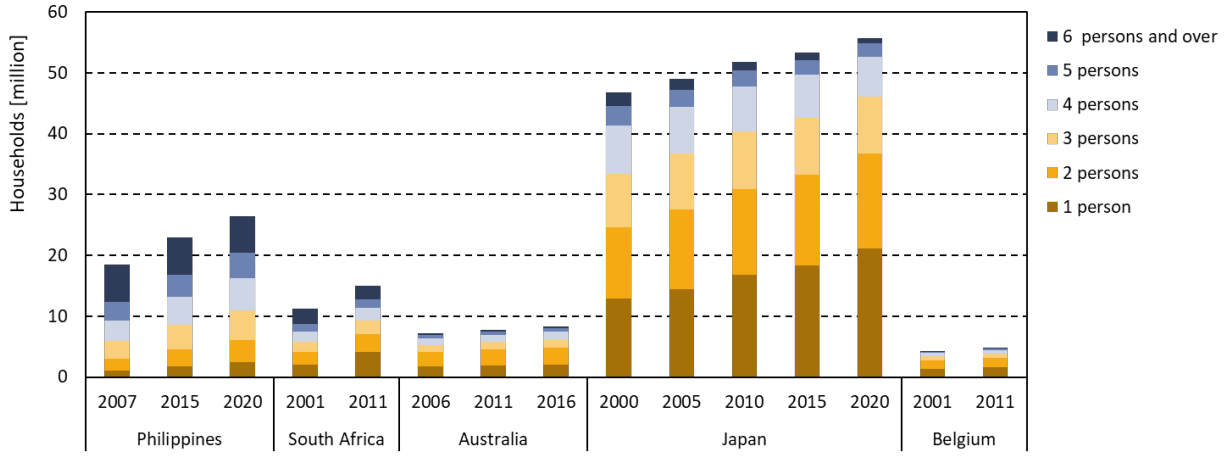


図 26　世帯人数別世帯数データの一部抜粋

(3)　住宅

RITE より，住宅種別居住人口・世帯データを提供していただいた．本データは，住宅種別（戸建・集合）の居住人口及び比率を統計実績値のある国について分析し，分析結果に基づき戸建居住人口比率を世界 54 地域区分について推計したものである．図 27 に各地域区分の 2020 年における推計値を示す．

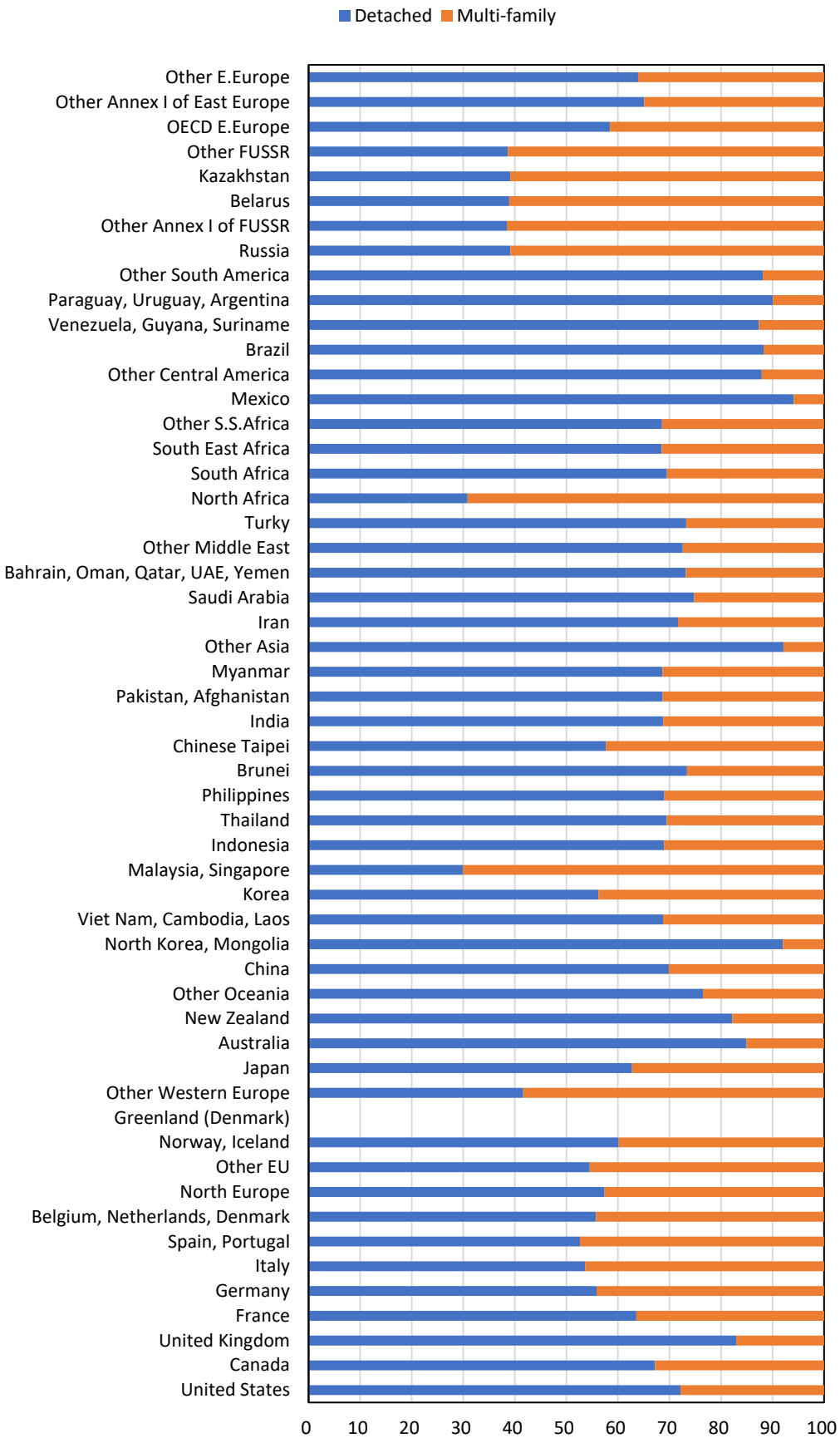


図 27　住宅種別居住人口比率の 2020 年推計値

4.2. 世帯の類型化

TREES モデルでは世帯を類型化し，各世帯類型のエネルギー消費量を推計してそれぞれの世帯数を乗じて積み上げることで各国のエネルギー消費量を推計する．表 2 に 12 の世帯類型を，図 28 に世帯類型別世帯数の推計フローを示す．

まず World Population Prospects 2022[10] より得られる推計対象年の人口を，平均世帯人数で除することによって世帯数を算出し，これに世帯人数比率を当てはめ世帯人数別世帯数を推計する．そして世帯人数別世帯数に戸建・集合居住人口比率を乗じることによって，世帯類型別世帯数を推計する．

表 2　世帯類型

世帯類型	世帯人数	世帯構成員	住宅仕様
世帯 1	1	単身	戸建
世帯 2	1	単身	集合
世帯 3	2	夫婦	戸建
世帯 4	2	夫婦	集合
世帯 5	3	夫婦＋子 1 人	戸建
世帯 6	3	夫婦＋子 1 人	集合
世帯 7	4	夫婦＋子 2 人	戸建
世帯 8	4	夫婦＋子 2 人	集合
世帯 9	5	夫婦＋子 3 人	戸建
世帯 10	5	夫婦＋子 3 人	集合
世帯 11	6	夫婦＋子 4 人	戸建
世帯 12	6	夫婦＋子 4 人	集合

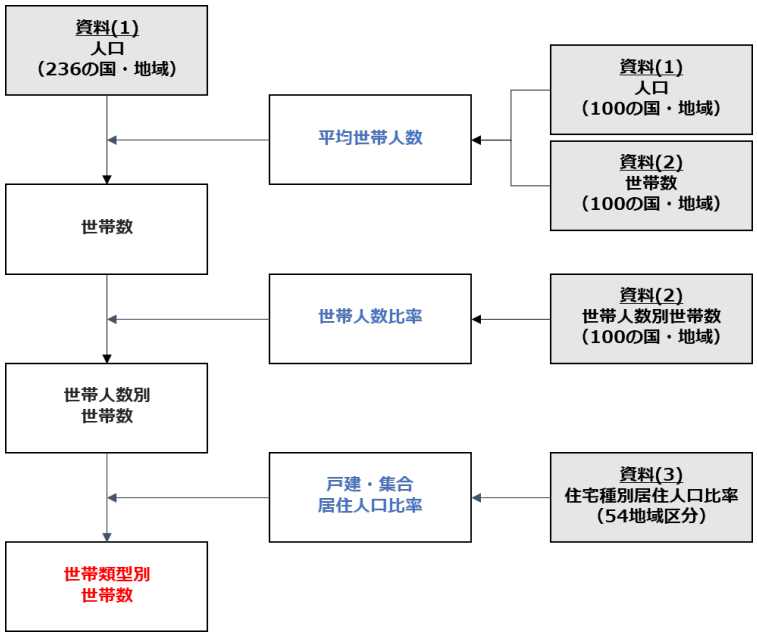


図 28　世帯類型別世帯数の推計フロー

(1)　平均世帯人数

まずDemographic Year Book[11]より，各国の最新年の世帯数を取得する．ただし現状や将来を推計するにあたっての乖離を小さくするため，2009年以降のデータのみを取得した．データが存在する123の国と地域のうち，2009年以降のデータが取得できたのは100の国と地域であった．この100の国と地域において世帯数を取得した年の人口を，World Population Prospects 2022[10]より取得した．人口を世帯数で除することによって，それぞれの国と地域における平均世帯人数を推計した．平均世帯人数が推計できない136の国と地域に関しては，1.3で述べる手法によって決定される近隣国の平均世帯人数を用いた．

(2)　世帯人数比率

平均世帯人数と同様に，Demographic Year Book[11]より，各国の最新年（2009年以降）の世帯人数別世帯数を取得し，100の国と地域それぞれの世帯人数比率を算出した．世帯人数比率が推計できない136の国と地域に関しては，1.3で述べる手法によって決定される近隣国の世帯人数比率を用いた．

(3)　戸建・集合居住人口比率

54地域区分のうち，各国が属する地域区分の住宅種別居住人口比率を適用した．

4.3. 平均世帯人数・世帯人数比率を適用する近隣国の選定方法

Demographic Year Book[11]より2009年以降の世帯人数別世帯数のデータを得られない136の国と地域には，他国の平均世帯人数及び世帯人数比率を適用する．適用する国を決定するにあたっては，隣国など地理的に近い国を選ぶ方法があるが，世帯人数の大きさは経済レベルとも相関があるのではないかと考え，検証を行った．各国の経済指標として，World Bank Income Groupを用いた．World Bank Income Groupは世界銀行の全加盟国189か国と人口3万人以上の28か国を，１人あたり国民総所得（GNI）によって分類する４つの所得グループ（High, Upper-Middle, Lower-Middle, Low）である[12]．

図 29にWorld Bank Income Group別の100の国と地域の平均世帯人数プロットを示す．経済レベルが低い国ほどばらつきが大きいものの，平均世帯人数が大きい傾向がある．図 30から図 33にヨーロッパ，アフリカ，アジア・オセアニア，アメリカ・カリビアンのWorld Bank Income Group別の世帯人数比率を示す．例外的な国もあるが全ての地域において，経済レベルが高いほど単身世帯の割合が大きく，低いほど6人以上世帯の割合が大きい傾向が読み取れる．

以上の結果から平均世帯人数や世帯人数比率など，世帯人数の大きさは経済レベルと関係していると考えられる．このことから，地理的な近さと合わせて経済レベルを考慮して平均世帯人数及び世帯人数比率を適用する国を決定することとした．

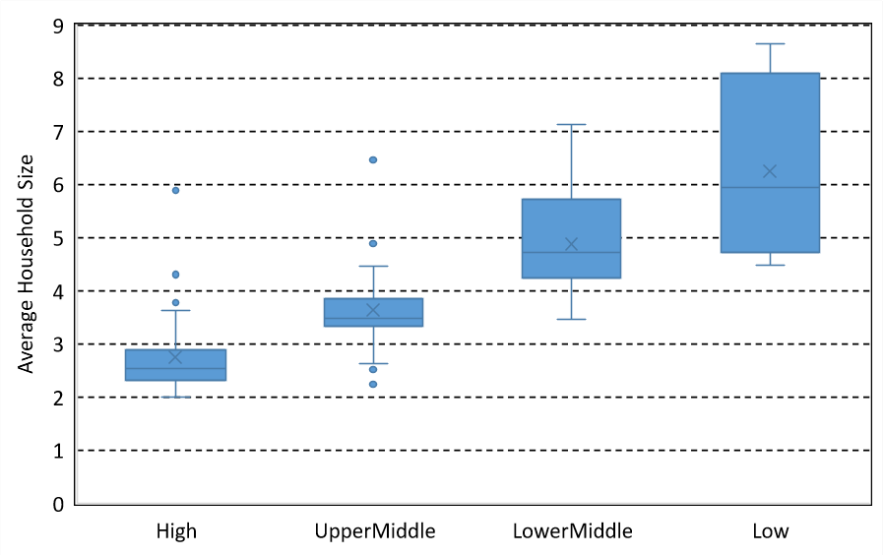


図 29　World Bank Income Group 別の平均世帯人数

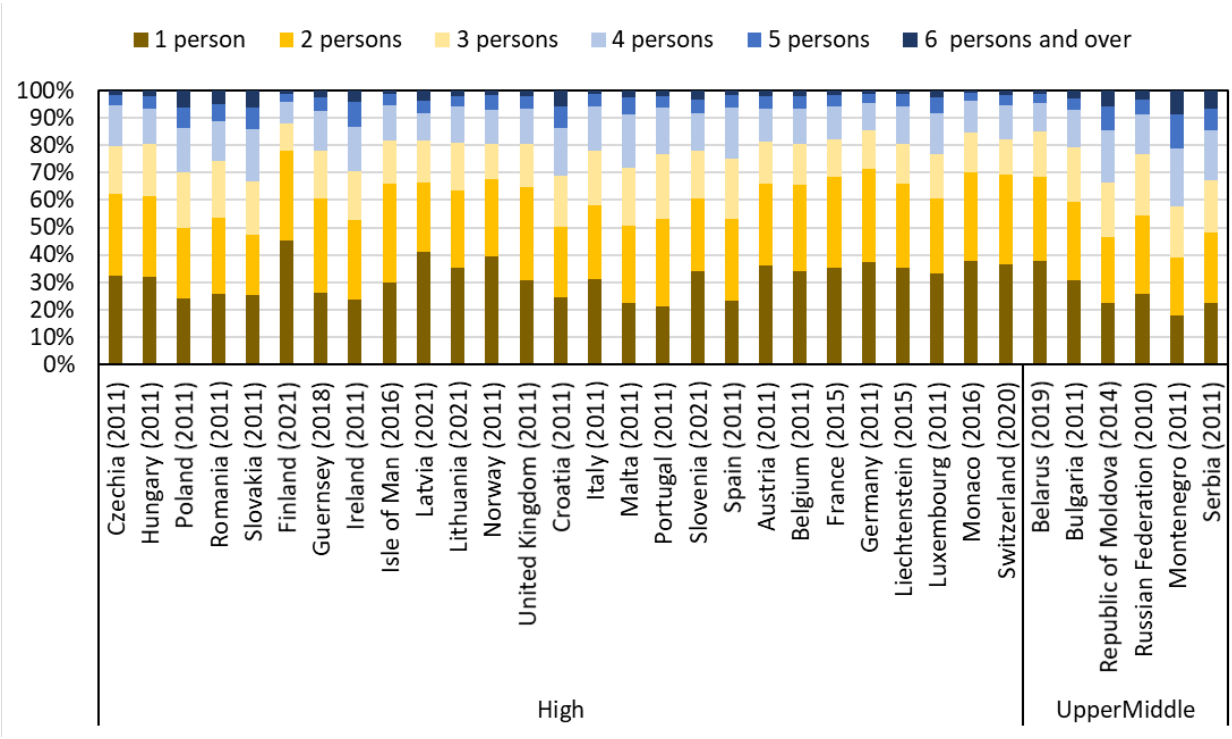


図 30　ヨーロッパにおける World Bank Income Group 別の世帯人数比率

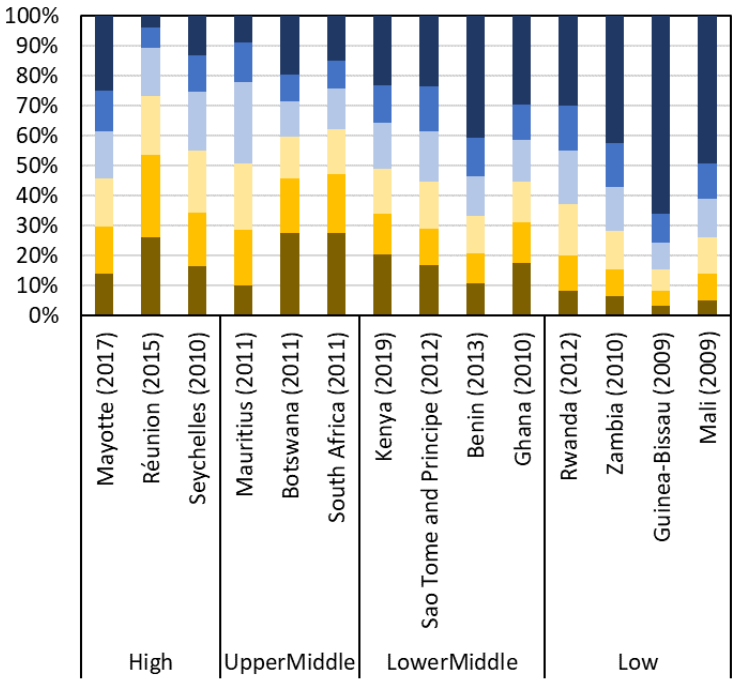


図 31　アフリカにおける World Bank Income Group 別の世帯人数比率

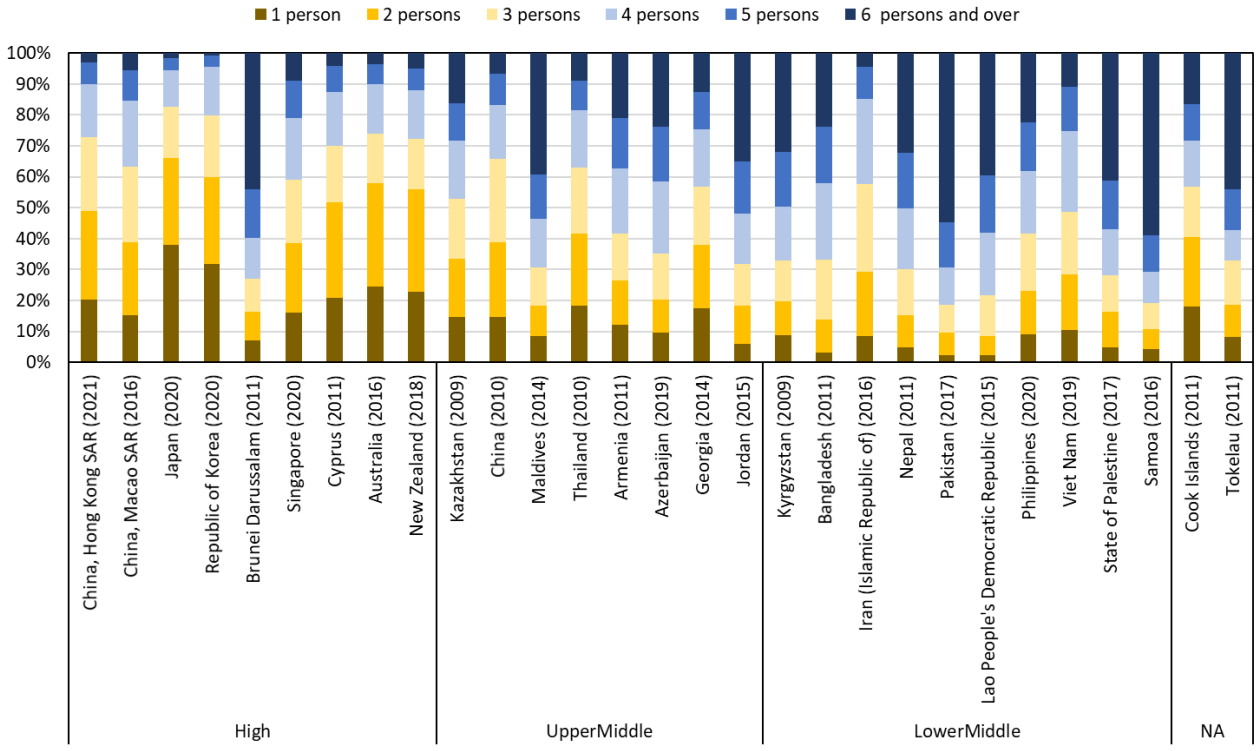


図 32　アジア・オセアニアにおける World Bank Income Group 別の世帯人数比率

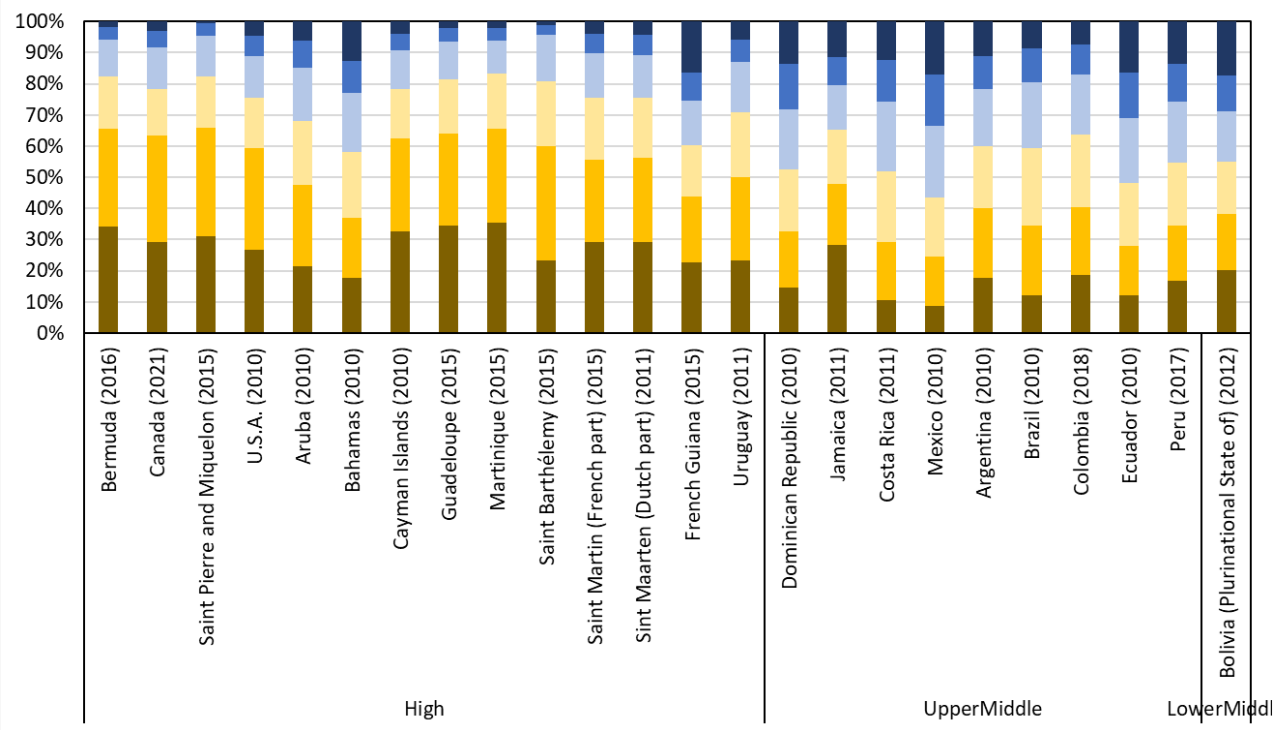


図 33　アメリカ・カリビアンにおける World Bank Income Group 別の世帯人数比率

5.　セントラルヒーティングモデルの開発

これまで TREES モデルは暖冷房を部屋単位で実施する個別空調方式を前提としていた．一方で，世界では一つの住宅，あるいは，建物で一つの熱源を持ち，各部屋に熱を配布するセントラルヒーティング方式が主流の国が多い．世界版への拡張のため，セントラルヒーティング方式をモデル内で考慮できるようにした．本節ではその検討内容を説明する．

セントラルヒーティングとは，一箇所の熱源機から建物全体に熱を送る暖房方式のことである．本研究で想定するセントラルヒーティングは灯油温水式，ガス温水式の 2 種類とする．これらのセントラルヒーティングは，ボイラによって温められた温水が管を通って各部屋に置かれたパネルヒータの中を流れることで輻射熱によって家全体を暖めるものである（図 34）． なお，管やパネルヒータは風呂などに使用される給湯とは別の独立した系である．

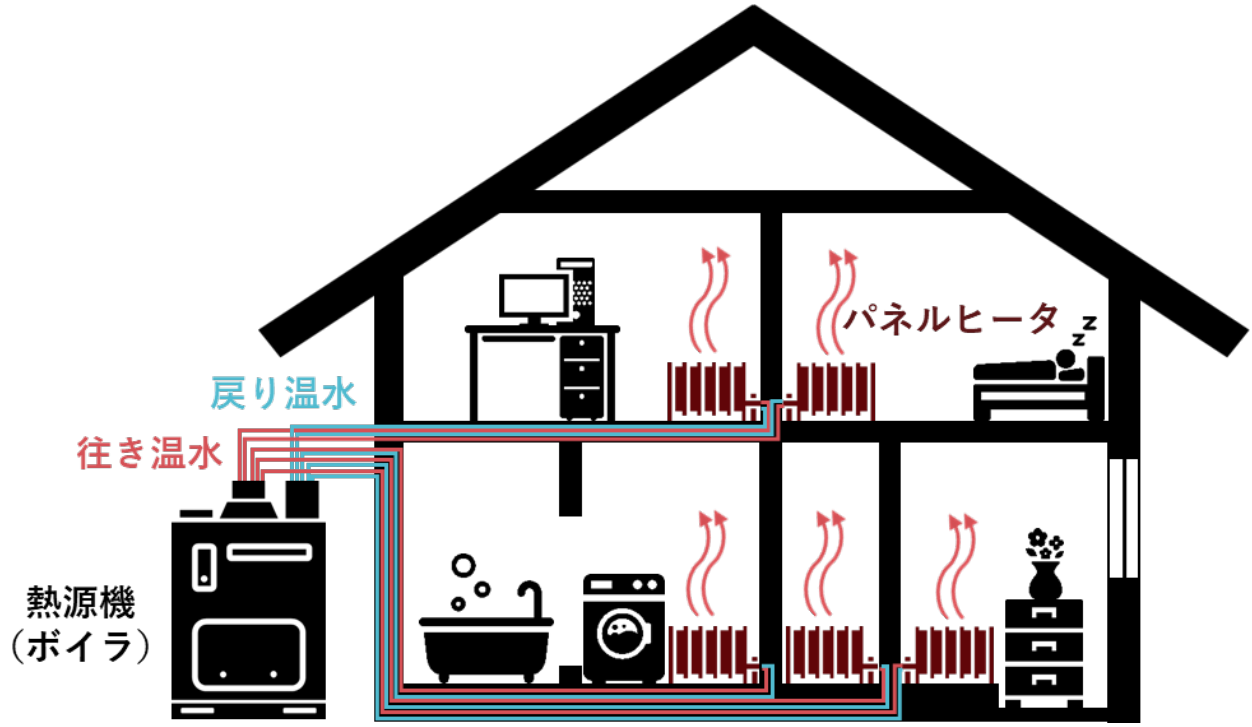


図 34　灯油温水式およびガス温水式セントラルヒーティング

セントラルヒーティングでは，図 34 に示すように廊下や風呂場など含む家全体を暖めることが多い．また，在室状況によってこまめに操作することなく 24 時間稼働させることが多い．家全体を暖めるためどの部屋でも同程度の室温を保つことができ，トイレや浴室などにおいて急激な温度変化によって起こるヒートショックを防ぐことが期待できる．また各部屋に暖房機器を設置する場合に比べて室内に露出する部分が少なくインテリアの美観を損なわない点[13]や，暖房効率を高めるために扉や仕切りを設置する必要性がないため間取りの自由度が上がる点[14]なども利点として考えられている．

5.1.　TREES モデルの計算仕様

TREES モデルでは住宅の各部屋においてタイムステップごとに暖房熱需要を算出し，それを暖房機器により処理することで部屋を暖める様子を再現している．図 35 に TREES モデルにおける暖房熱処理の概要を示す．TREES モデルでは各世帯について，建物のスペック，気象データ，保有している家電機器，居住者行動といった入力データが存在し，入力データをもとに各部屋・各タイムステップの熱取得および熱損失が決定している．熱取得と熱損失から導かれた暖房熱需要を入力として，各暖房機器の熱処理計算によって処理熱量が決定し，それにより室温が決定する．各タイムステップにおける室温は，次のタイムステップの計算で前タイムステップの室温として用いられる．

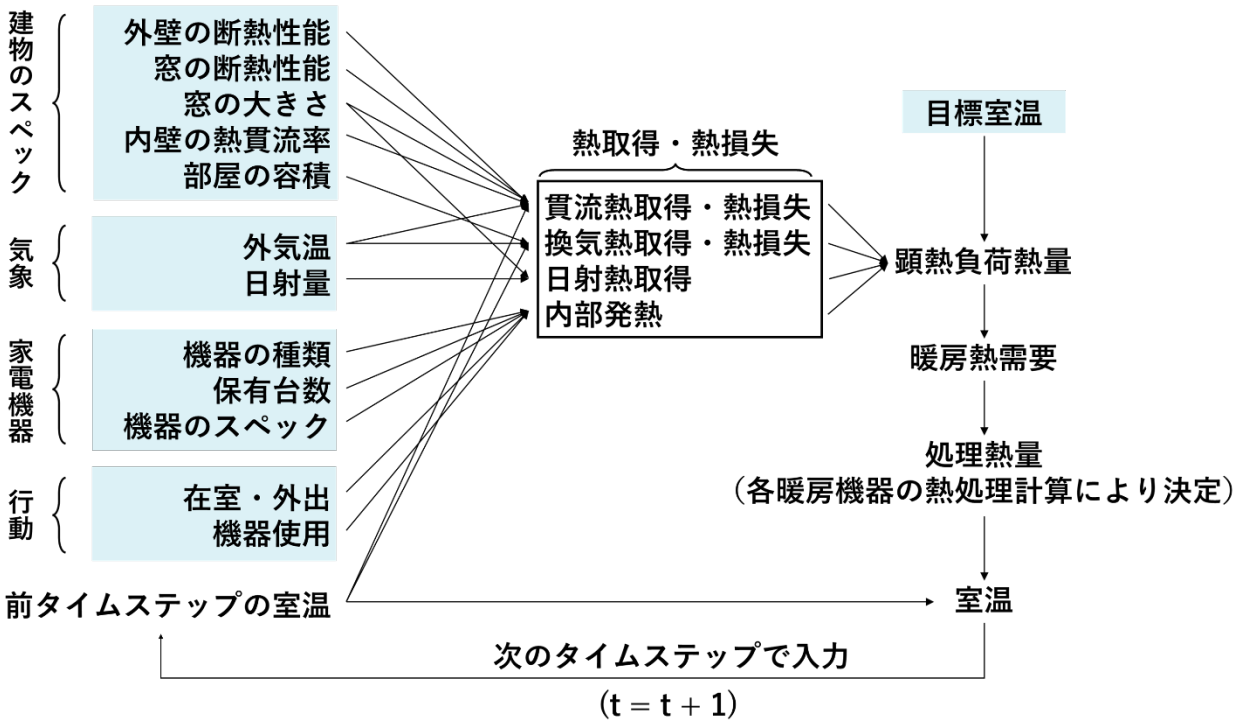


図 35　TREES モデルの推計値と CO_2 排出実態統計調査の値の比較

各機器の熱処理計算では，暖房熱需要をもとに処理熱量およびエネルギー消費量が決定される．例として図 36 に灯油ヒーターおよびガスヒーターの熱処理計算のフローを示す．灯油ヒーターおよびガスヒーターでは，機器のスペックとして最小出力，最大出力，効率があらかじめ決まっている．暖房熱需要が最小出力未満であった場合，処理熱量は最小出力に等しくなる．また暖房熱需要が最大出力以上であった場合，処理熱量は最大出力に等しくなる．暖房熱需要が最小出力以上かつ最大出力未満であった場合，処理熱量は暖房熱需要に等しくなる．以上のようにして決まる処理熱量に効率の逆数をかけることによって，エネルギー消費量を算出する．その他の暖房機器についても，処理熱量の決定方法や効率の決定方法は異なるものの暖房熱需要を入力として処理熱量とエネルギー消費量が決定するという流れは同様である．

TREES モデルにおける暖冷房の ON/OFF は，在室者の有無や就寝中かどうかなどの複数の条件によって決定されている．

図 37 に暖冷房 ON/OFF 決定のフローの一部を示す．

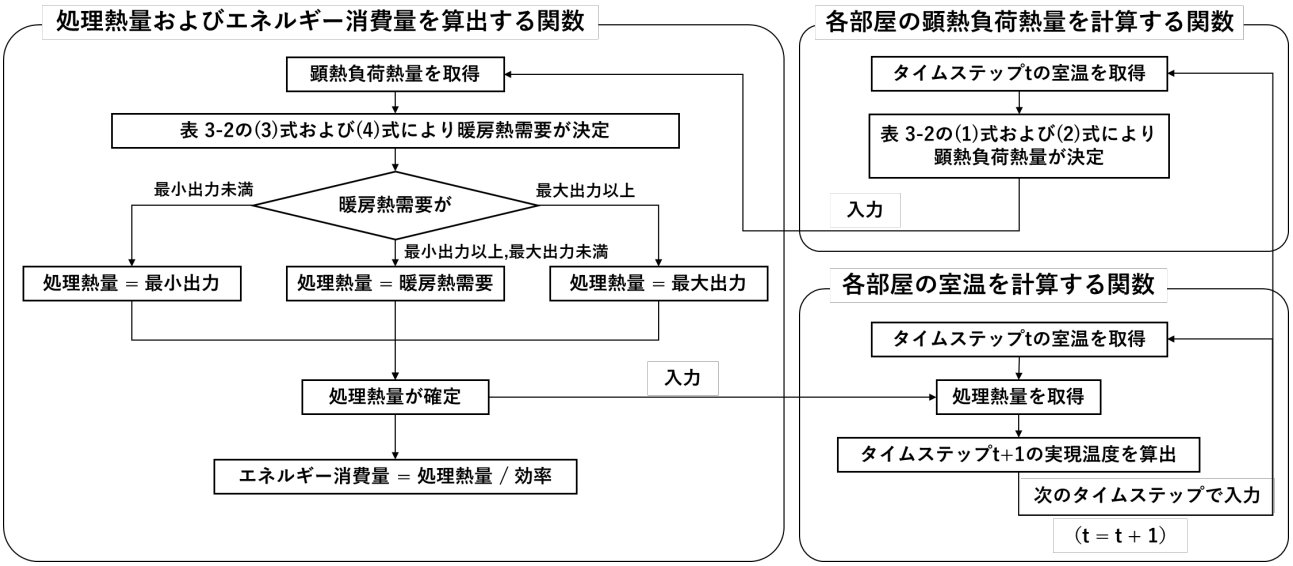


図 36　灯油ヒーターおよびガスヒーターの熱処理計算のフロー

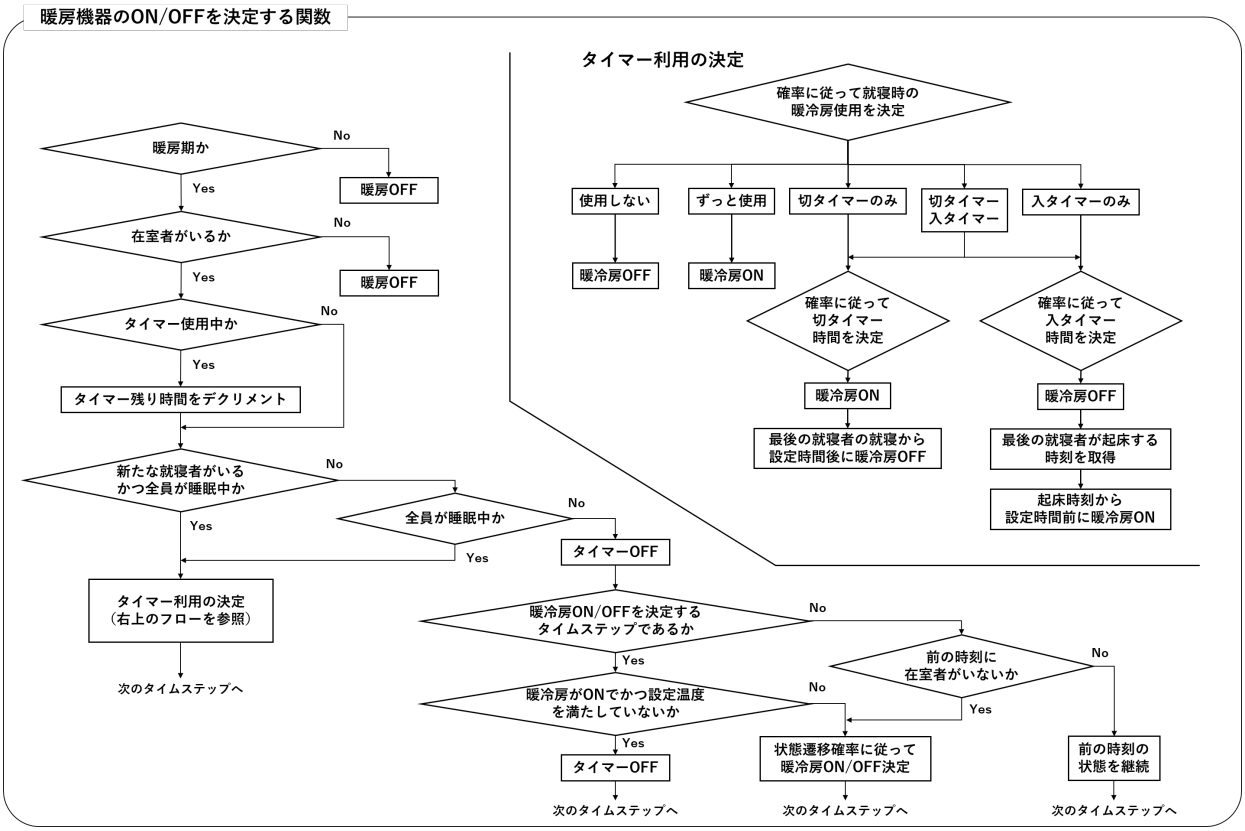


図 37　　従来の暖房機器の ON/OFF 決定フロー

5.2.　セントラル方式の考慮

TREES モデルへの実装について詳細に説明する．実装はセントラルヒーティングの熱処理計算，24 時間稼働，空調空間の見直しの 3 段階に分けて行った．各段階の詳細な内容を以下で述べる．

（1）セントラルヒーティングの熱処理計算

セントラルヒーティングの熱処理計算のフローを図 38 に示す．図 38 からわかるように，機器の最小出力や最大出力を設けず，処理熱量は暖房熱需要と等しくなるように熱処理計算を行う．すなわち，各タイムステップに算出された暖房熱需要はそのタイムステップに全て処理されることを仮定している．エネルギー消費量は処理熱量に効率の逆数をかけることで算出することとし，効率はエネルギー消費性能計算プログラム [15] を参考に，灯油温水式の場合は 0.82，ガス温水式の場合は 0.81 とした．

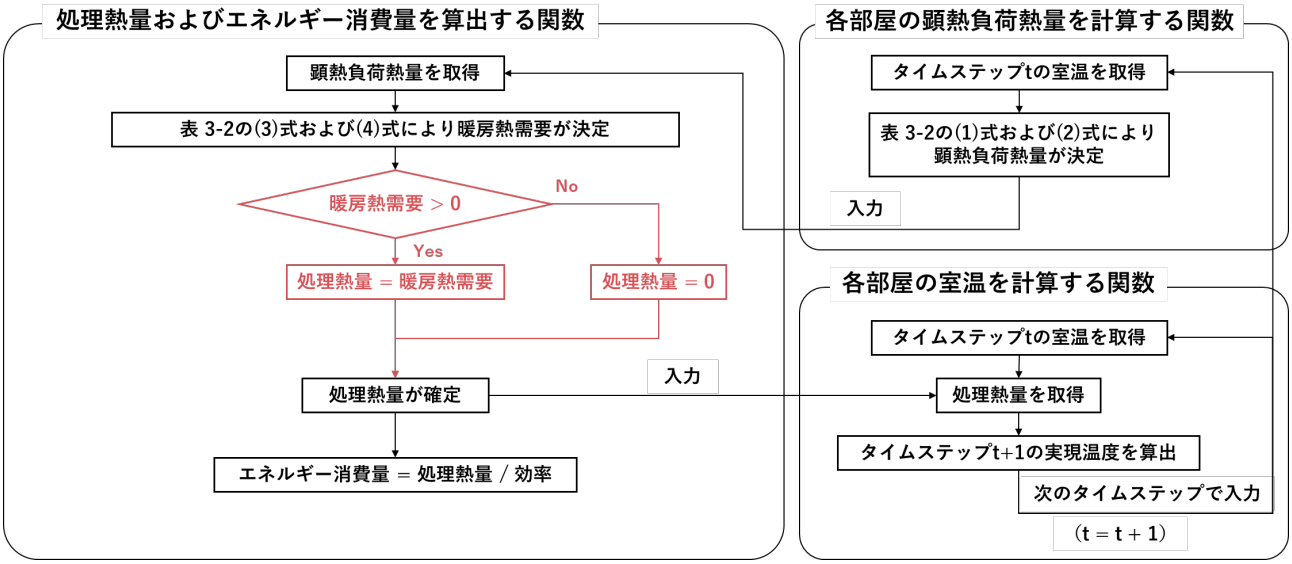


図 38　セントラルヒーティングの熱処理計算のフロー

（2）24 時間稼働の実装

本研究ではセントラルヒーティングの特徴を再現するため，セントラルヒーティングであれば 24 時間稼働とする機能を追加した．変更後のフローを図 39 に示す．図のフローに変更することにより，セントラルヒーティングの場合は 24 時間稼働し，それ以外の暖房機器の場合は従来通りの方法で ON/OFF 決定がなされるようにした．

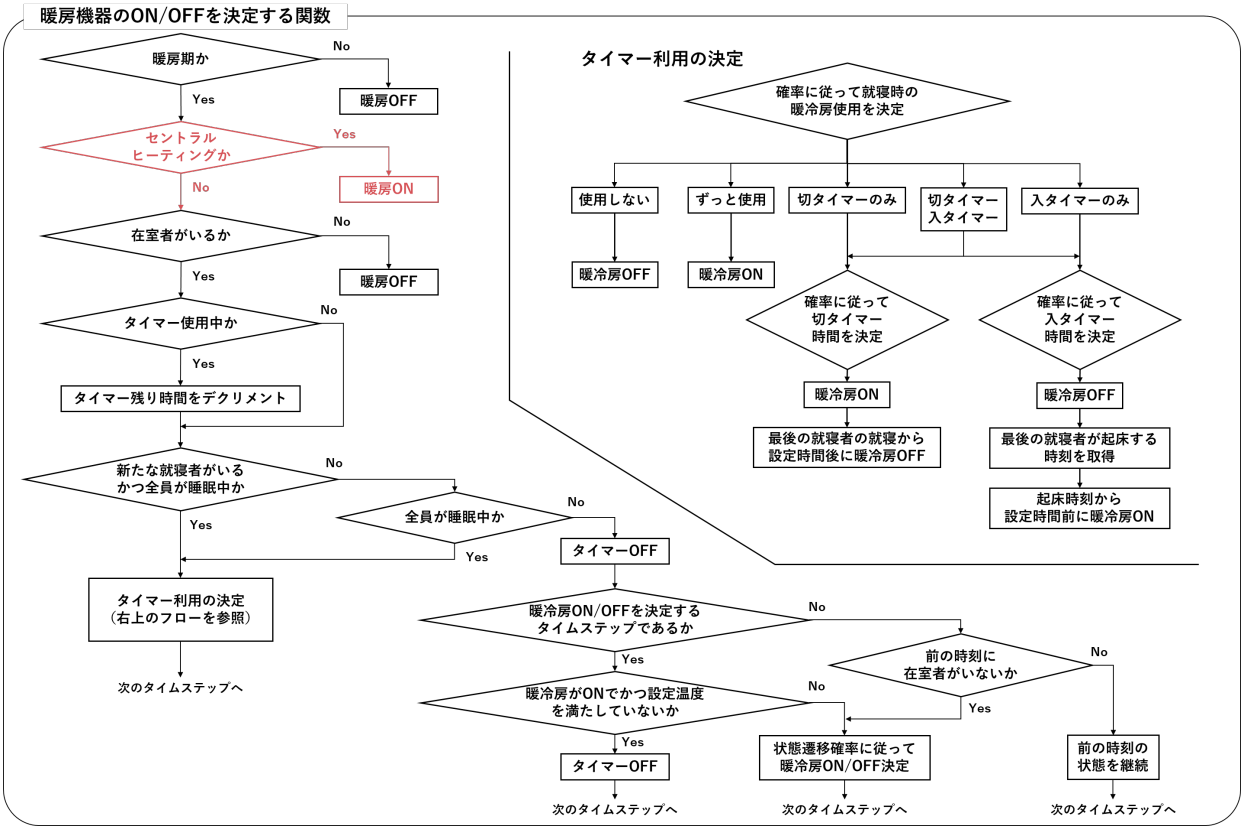


図 39　変更後の暖房機器の ON/OFF 決定フロー

（3）空調空間の見直し

TREES モデルにおける暖房機器は居間や寝室などの個室にのみ設置されていた．本研究でのセントラルヒーティングの実装においては特徴を再現するために，これらの個室に加えて厨房，洗面所，浴室，廊下，トイレなどの空間も暖めるようにした．

5.3.　検証

本節ではセントラルヒーティング実装の検証について述べる．同一条件の世帯について，使用する暖房機器がセントラルヒーティングの場合の暖房需要とそうでない場合の暖房需要を比較して妥当性を検討した．

（1）方法

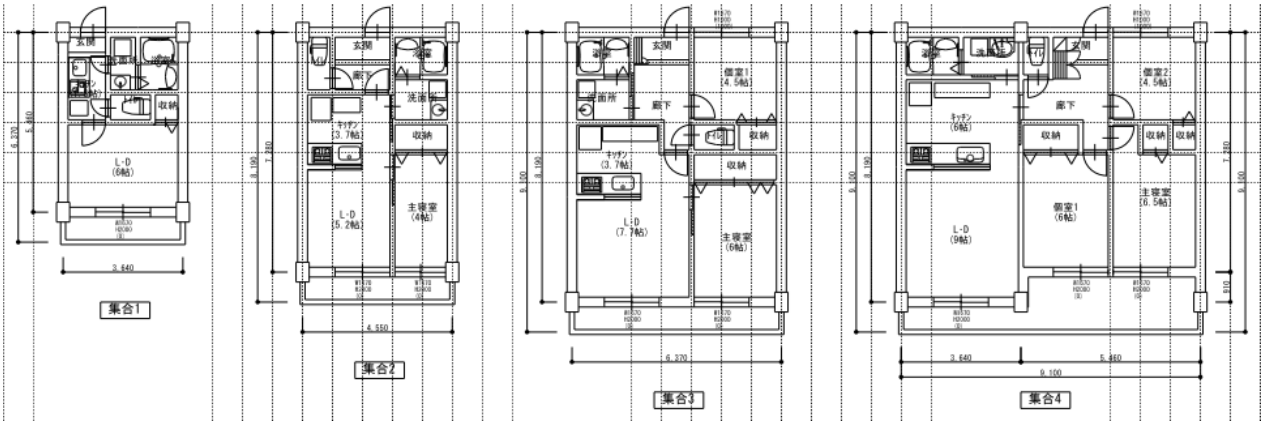
対象とした世帯の設定条件を表 3 に示す．表に示す通り，住宅類型は集合 1～集合 6 および戸建 1～戸建 6 の 12 種類を，断熱性能は無断熱，旧基準，新基準，次世代基準，ZEH 基準の 5 種類を考慮した表 4 および図 40 に示すように，住宅類型は数字が大きいものほど部屋数が多く，延床面積も大きい．なお世帯人数は，各住宅類型の部屋数と等しいものとした．また暖房機器は，セントラルヒーティング保有世帯では灯油温水式セントラルヒーティング，非保有世帯では灯油ヒーターを保有することとした．

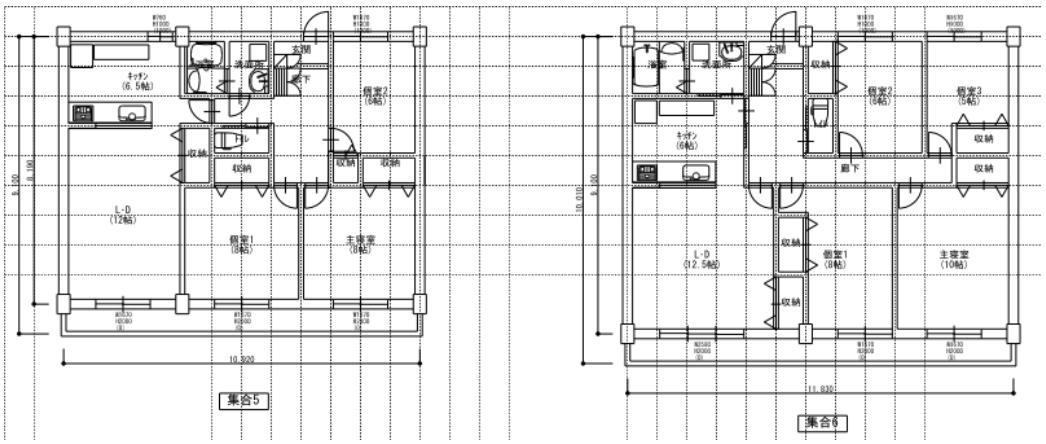
表 3　検証の対象世帯の条件設定

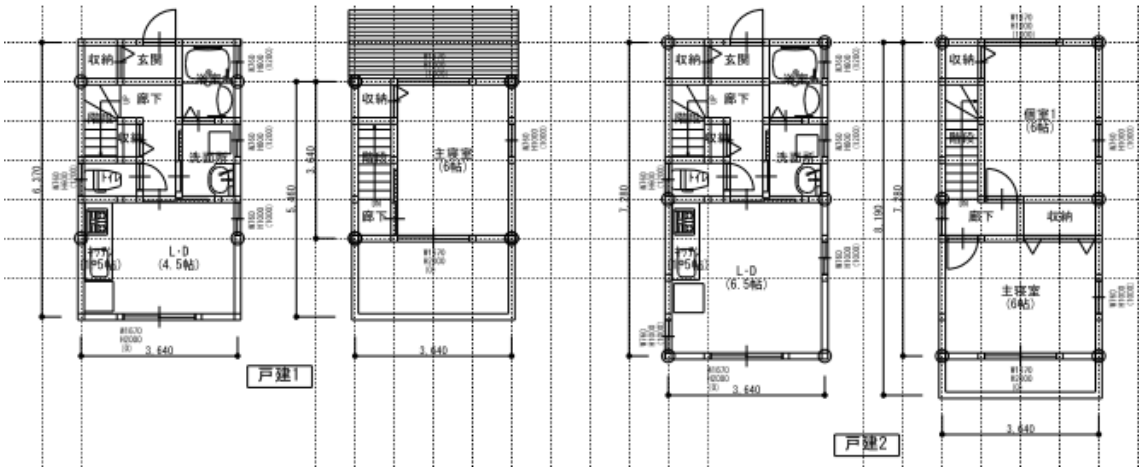
項目		条件設定
固定	地域	北海道
	推計対象年	2018年
可変	住宅類型	集合1~6，戸建1~6
	断熱性能	無断熱，旧基準，新基準，次世代基準，ZEH基準

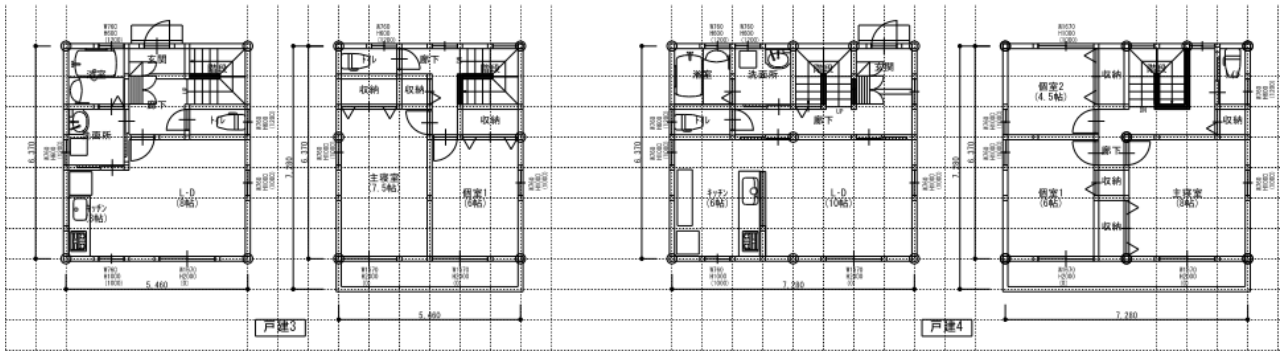
表 4　各住宅類型の部屋数および部屋別床面積

住宅類型	間取り	床面積 [m^2]												
		居間	厨房	浴室	洗面	トイレ1	トイレ2	主寝室	個室1	個室2	個室3	個室4	廊下・階段他	合計
集合1	1K	9.94	2.48	2.48	1.66	1.24							2.07	19.87
集合2	1LDK	8.70	6.21	2.48	2.48	1.66		6.62					4.97	33.12
集合3	2LDK	12.84	6.21	2.48	2.48	1.24		9.94	7.45				7.04	49.68
集合4	3LDK	14.91	9.94	2.48	2.48	1.24		10.77	9.94	7.45			7.87	67.08
集合5	3LDK	19.87	10.77	2.48	2.48	1.66		13.25	13.25	9.94			10.77	84.47
集合6	4LDK	20.70	9.94	3.31	3.31	1.66		16.56	13.25	9.94	8.28		14.08	101.03
戸建1	1LDK	7.45	2.48	2.48	2.48	1.24		9.94					9.53	35.60
戸建2	2LDK	10.77	2.48	2.48	2.48	1.24		9.94	9.94				11.18	50.51
戸建3	2LDK	13.25	4.97	3.31	3.31	3.32		12.42	9.94				15.74	66.26
戸建4	3LDK	16.56	9.94	3.31	3.31	1.66	1.66	13.25	9.94	7.45			21.53	88.61
戸建5	4LDK	16.56	9.94	3.31	3.31	1.66	1.66	13.25	9.94	9.94	9.94		24.84	104.35
戸建6	5LDK	22.36	9.94	3.31	3.31	1.66	1.66	16.56	13.25	9.94	8.28	10.77	22.36	123.40




集合5
集合6


戸建1
戸建2


戸建3
戸建4

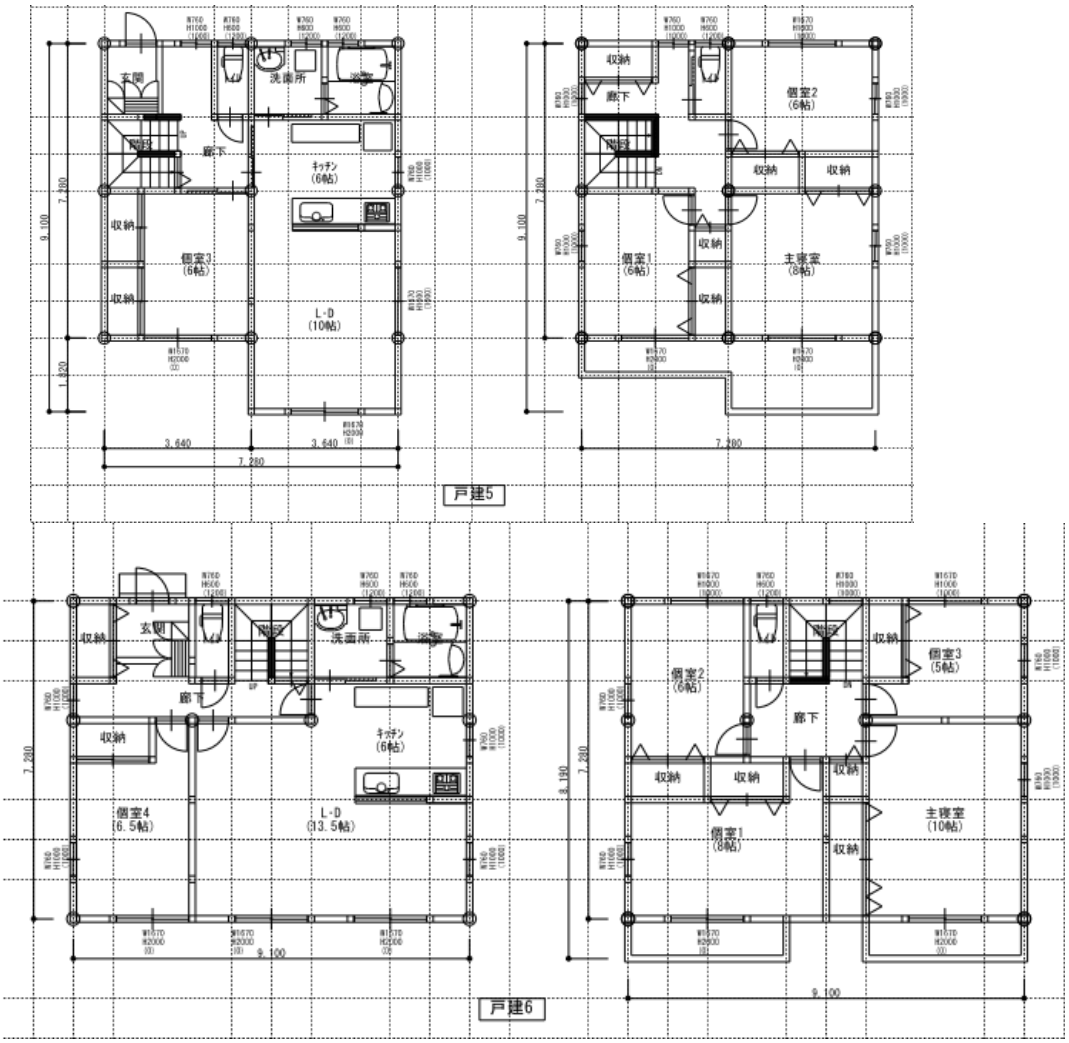


図 40　各住宅類型の平面図

（2）結果

灯油ヒーターを使用する場合と灯油温水式セントラルヒーティングを使用する場合とで，一日の暖房需要の変化の様子を比較した．例として住宅類型が戸建 4，断熱性能が旧基準，世帯人数が 4 人の住宅における 2018 年 1 月 9 日の暖房需要の推計値を図 41 および図 42 に示す．ただし，図 41 は灯油ヒーターを使用する場合，図 42 は灯油温水式セントラルヒーティングを使用する場合の推計値である．なお，ここでは暖房需要の変化の解釈を容易にするため 4 人の居住者は同じ時刻に起床，外出，帰宅，就寝するように設定してある．以下で暖房需要の変化の解釈について具体的に説明する．

図 41 では，起床，帰宅，就寝といった居住者行動と図 39 のフローに従って暖房の ON/OFF が決定され，それに伴い暖房需要が発生している．例えば 15 時に帰宅した時には暖房が ON になっていることがわかる．このとき，冷えていた部屋を目標室温まで暖めようとするため比較的大きな暖房需要が生じるが，目標室温に達した後はそれを維持するための比較的小さな暖房需要が続くことになる．その後 16 時半ごろに一度暖房は OFF になったが，19 時半ごろに再び ON になり，同じように短時間の比較的大きな暖房需要が生じている．21 時ごろに就寝のために 4 人がそれぞれの部屋に移動してそれぞれの部屋で暖房を使用することにより，日中に比べて大きな暖房需要が発生している．

一方，灯油温水式セントラルヒーティングを使用した図 42 では，図 39 のフローに従って居住者行動に依らず常に全ての部屋で暖房が ON となる．そのため，灯油ヒーターを使用する場合のような短時間の暖房需要の局所的なピークは見られず，継続的に大きな暖房需要が発生している．一日の暖房需要の合計値は 1.95 倍になった．このような暖房需要の変化の様子から，実装したセントラルヒーティングモデルは現実のセントラルヒーティングの挙動を再現できていると考えられ，モデルはある程度妥当なものであると考えられる．

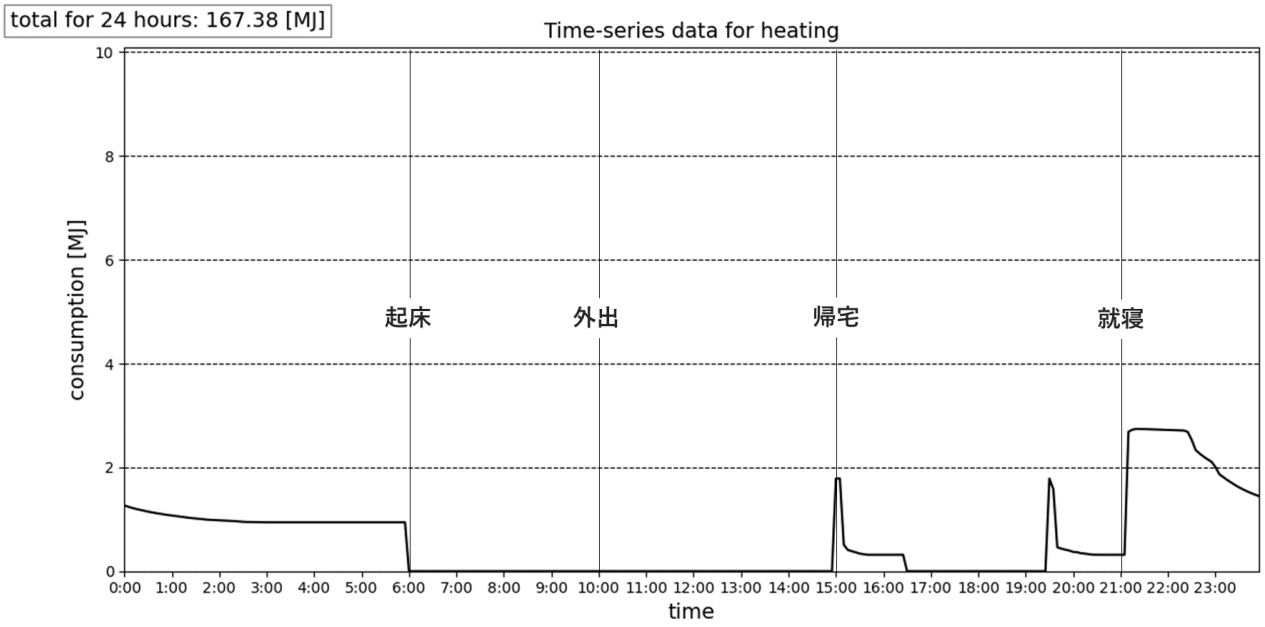


図 41　一日の暖房需要の推計値（灯油ヒーターを使用する場合）

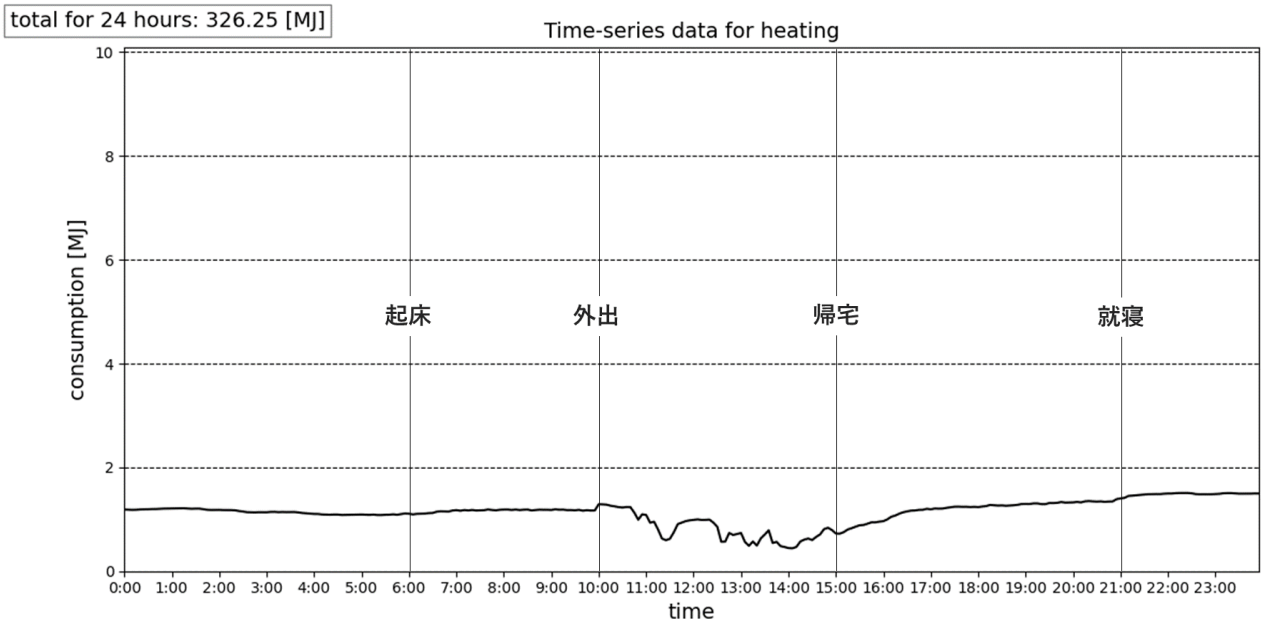
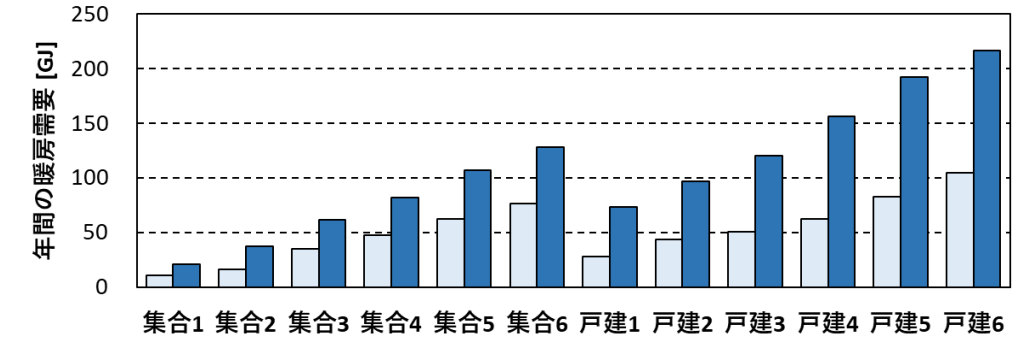


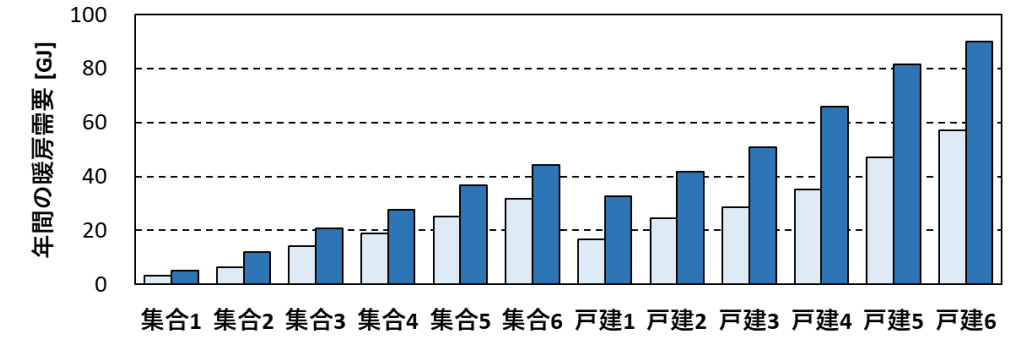
図 42　一日の暖房需要の推計値（灯油温水式セントラルヒーティングを使用する場合）

次に，灯油ヒーターを使用する場合と灯油温水式セントラルヒーティングを使用する場合とで年間の暖房需要推計値を比較した．各世帯の年間の暖房需要推計値の比較を図 43 に示す．いずれの世帯においても灯油温水式セントラルヒーティングの暖房需要が大きい結果となった．この増加は，灯油ストーブでは在室者の有無や就寝中かどうかなどの複数の条件によって ON/OFF が決定するのに対してセントラルヒーティングでは 24 時間暖房が稼働することや，灯油ストーブによっては暖められない廊下やトイレなども暖房されることに起因する．また住宅類型別にみると，集合と戸建それぞれで床面積が大きいほど暖房需要が大きい結果となった．集合と戸建の間，例えば集合 3 と戸建 1 では，戸建 1 の床面積が小さいにもかかわらず暖房需要が大きいが，これは集合住宅では住宅の一面または二面のみが外気に接する設定であるのに対して戸建住宅では四面ともが外気に接する設定であることにより，戸建住宅の貫流熱損失が大きくなっているためだと考えられる．断熱性能別では，断熱性能が向上するほど暖房需要が小さいことが確認できる．以上のように，想定に反する結果は見られなかったため，セントラルヒーティングモデルの実装は妥当なものであると判断した．

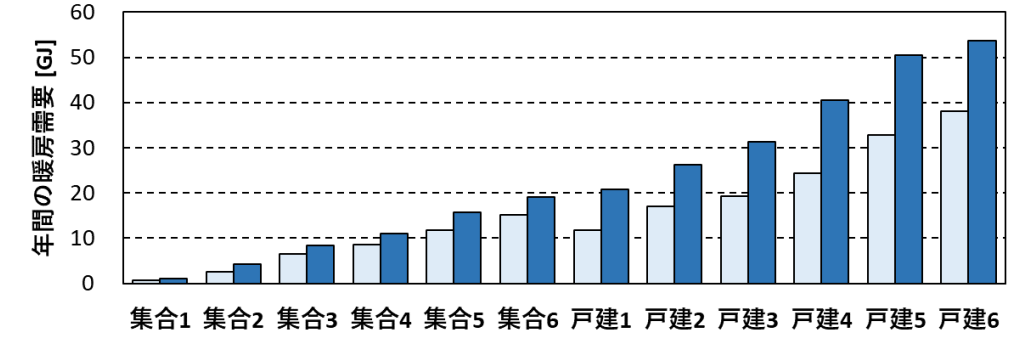
無断熱



旧基準



新基準



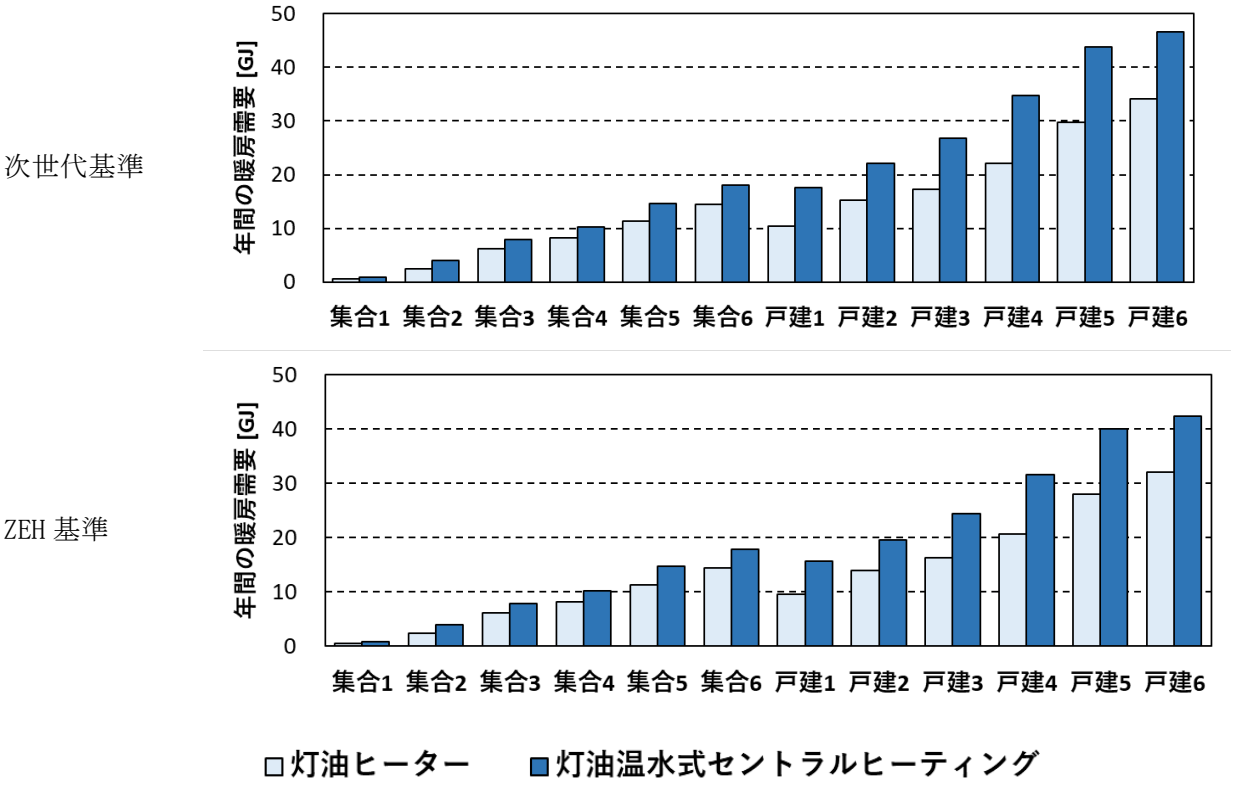


図 43　年間の暖房需要推計値の比較

6. まとめ

本報告書では 2023 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．

- Climate.OneBuilding.org が配布する世界の代表的都市の典型気象データを用いることによって典型的なエネルギー需要の推計値を得ることができる．TREES 世界版では同典型気象データを用いてエネルギー需要の推計を行うこととする．
- TREES 世界版では，各世帯類型についてエネルギー需要を推計し，世帯数を乗じて積み上げることで世界各国の家庭部門エネルギー需要を推計する．このため，人口・世帯・住宅に関する統計資料に基づいて世界 236 の国と地域の世帯類型別世帯数についてデータを整理した．
- 特に寒冷地で多く用いられているセントラルヒーティングを TREES モデルにおいて実装し，その動作がある程度妥当であることを確認した．加えて，セントラルヒーティングでは部屋単位で暖房を行う個別暖房方式と比較して暖房面積が増加し，稼働時間が長くなることにより年間の熱負荷が増加し，その結果としてエネルギー需要が増加することを確認した．

今後，その他のエネルギー需要決定要因についての調査を行い，データベースを整備する．そのうえで，技術やライフスタイルの変化によるエネルギー需要の変化を推計可能なモデルを確立する．

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Social innovation enablers to unlock a low energy demand future

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Abstract

We initiate the process of developing a comprehensive Low Energy Demand (LED) innovation narrative by applying the framework "Functions of Innovation Systems" (FIS) and identifying 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 potential for LED-focused mitigation is much larger than previously portrayed and have shown 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 end-use sectors: industry, transport, and buildings. Our analysis relies on the FIS approach to assess three innovations in these sectors. A key insight is that the distinct characteristics of LED technology make enabling social innovations crucial for their widespread adoption. Finally, we identify a set of eight social enablers required for unlocking LED pathways.

1. Introduction

The LED scenarios (Grubler *et al* 2018) quantitatively showed that LED technologies and behaviors could reduce emissions over the next 30 years compatible with a 1.5C target. They used detailed estimates of how low energy use could become across the whole economy and then used Integrated Assessment Modelling (IAMs) to evaluate mid-century impacts on greenhouse gas emissions and other social indicators. It built on earlier efforts going back to the 1970s, for example Soft Energy Paths (Lovins 1976), as well as the International Energy Agency's longstanding work on energy efficiency (IEA 2022), but is distinct because of its low temperature target. The LED results are important because they showed that the scope of emissions savings through lower energy use is vast, to the extent that they enabled the Paris Agreement targets to be achieved without relying on technological carbon removal. These insights arose from the authors' distinct focus on energy services and whence energy demand arises–particularly in the context of increasing access to energy services in developing countries.

The original LED paper had a substantial impact on the climate community. For example, its insights were prevalent in the IPCC AR6 chapter on energy demand (Creutzig *et al* 2022b). However, one prominent critique is that while the paper calculated careful estimates of energy savings, it did not make claims about how realistic achieving those savings might be (Keyßer and Lenzen 2021). While (Grubler *et al* 2018) compared energy use in today's world to that in the LED future through IAMs scenario runs, it did not explicitly characterize how behavioral and social dynamics would enable the transition to a low-energy world (Cordroch *et al* 2022). For example, it provided only an overarching view of how digital technologies may impact energy demand from industry and adopted a quite specific focus on energy savings due to the increasing role of services in meeting consumer choices. This set of mechanisms is particularly important given the LED scenario's emphasis on energy end-use, the role of consumers, and especially how they interact with each other. The extent to which LED approaches are taken seriously as credible complements to other mitigation efforts depends on understanding whether a LED world can be realistically attained over the next three decades; this in turn depends on a better characterization of the mechanisms for a transition to an LED world, which we describe here as LED innovation.

In this paper, we initiate the process of building a comprehensive narrative on LED innovation that describes how LED technologies can improve and be scaled up to become widely adopted. Following (Nemet and Greene 2022), LED innovations are defined as "any effort to improve the level and structure of energy demand", "including LED technologies and LED services." This broad definition allows us to depart from a purely technological focus towards the inclusion of human behavior and business models. We rely on the "Functions of Innovation Systems" (FIS) framework (Bergek *et al* 2008) to identify innovation dynamics and adoption timelines consistent with overall LED scenarios. This allows us to identify conditions and key enablers for the successful development and deployment of LED innovation in the context of five key drivers of change that condition innovation in low energy demand (Grubler *et al* 2018): higher living standards, urbanization, digitalization, novel services, and prosumers. This paper thus represents a first step towards the generation of narratives characterized by a comparative systemic perspective through both quantitative indicators and qualitative descriptors to appropriately capture the many ways LED futures could unfold, given the distinct characteristics of LED innovations (Nemet and Greene 2022).

2. Methodology and scope

2.1. Analytical approach

Following Grubler et al. (2018), we focus on three key high-level sectors— buildings, transport, and industry—because they provide a useful taxonomy congruent with the structure of IAMs. Essential improvements in terms of LED and decarbonization also arise when these sectors are coupled, such as vehicle-to-grid applications (Sovacool et al., 2020). In addition, general purpose

technologies with pervasive effects across sectors also play a key role, e.g. digitalization (Creutzig *et al* 2022a, Wilson *et al* 2020b).

Our comparative case study analysis of innovations relevant in the context of a LED[1] follows the approach of (Hekkert *et al* 2007), which identifies seven key functions of innovation systems: knowledge development, knowledge diffusion, the guidance of search, resource mobilization, entrepreneurial activities, market formation and creation of legitimacy. We conceptualize how the development from nascent adoption to widespread diffusion of three innovations—which differ in innovation stage and maturity—may support the achievement of LED with a specific focus on the relevance of the different functions, and the role that key actors will play in LED scenarios in various sectors. While other innovations are also relevant in the context of LED, the three examples we discuss here are both relevant for their impact on energy demand, and widely discussed in both academic and business circles. A main insight from this comparative approach is that successful LED innovations involve substantial contributions from, and interactions among, technological, social, and business model innovation. This ultimately leads us to identify and discuss key enablers and conditions for further development and widespread uptake relevant for modelling LED pathways.

2.2. Distinct characteristics of LED innovations

A set of characteristics makes LED innovations distinct from many other types of innovation (Nemet and Greene 2022). In our context, these can be summarized as follows:

1. LED innovations favor a movement from a traditional economy based on goods towards the provision of ***Services*****.** However, more efficient service provision can stimulate more utilization through short-term and longer rebound effects. Yet , typically, rebound takes back only some of the energy savings but not all (Gillingham *et al* 2016).

2. In contrast to supply-side approaches, LED adoption involves the successful and widespread application across billions of heterogeneous ***Adopters*** with diverse preferences for services (Niamir *et al* 2020b, Nemet and Greene 2022). Individual energy-related decisions, adopting new technology or services, are influenced by peer effects, norms and values (Creutzig *et al* 2022b, Niamir *et al* 2020c, Hicks and Ison 2018, Devine-Wright 2011).

[1] LED innovations encompass all endeavors aimed to improve the level and structure of energy demand, including advancements in LED technologies and associated LED services. This broad definition expands the system boundaries of our analysis: from a purely technological focus towards the inclusion of human behavior and business models; from a pure focus on energy to consideration of material use impacts; and from a mere focus on monetary indicators (e.g., GDP) towards inclusive well-being. Our working assumption is that successful LED innovations are likely to involve substantial contributions from, and interactions among, technological innovation, social innovation, and business model innovation.

3. LED ***Technologies*** are typically small in unit size and thus characterized by (a) strong potential for cost reductions and customization through iterative modification and adaptation, (Wilson *et al* 2020a, Sweerts *et al* 2020) and (b) amenable to new business models in the circular economy. Importantly, general purpose technologies such as digitalization can pervasively enhance LED services (Wilson *et al* 2020c).

2.3. Case study selection

Among the many possible cases, we selected one for each sector, which has potential to contribute to LED. Table 1 provides an overview of the main characteristics of the three case studies: additive manufacturing (AM), which has the potential to revolutionize the production of goods within the industrial sector; sharing mobility (SM) as a cutting-edge service within the transportation sector; and household energy users producing electricity with rooftop solar to become solar prosumers (SP) in the realm of building infrastructure. These cases exhibit distinct characteristics, including the nature of the services, adopters, and technologies. They also represent varying stages of innovation, while all three hold significant promise for reducing energy demand. Another vital factor guiding our selection process was the need to illustrate the diverse roles of enabling conditions in expediting adoption by end-users.

Table 1. *Summary characteristics of the case studies*

Case study	**Additive manufacturing (AM)**	**Sharing mobility (SM)**	**Solar prosumers (SP)**
Sector	Industry	Transport	Buildings
Innovation focus	technical, business model	infrastructural, technical, business model, regulation	technical, infrastructural, business model, regulation
Innovation stage[1]	Market adoption and scale-up in niche markets for specialized applications. Fundamental science and technology exploration to prototyping for other applications.	From prototype to market adoption and scale-up, depends on the mobility mode and geographical context (e.g. urban/rural, developing/developed countries)	Technology mature. Consumer adoption nascent.
Distinct characteristics	Services: change from traditional production to made-on-demand, customized products. Adopters: Firms Technology: 3D printing	Services: sharing mobility infrastructure and business (e.g., GoGet, Lime micro-mobility) Adopters: Citizens Technology: the mobile	Services: renewable electricity Adopters: Citizens Technology: solar PVs,

		applications	batteries, electric grid
Key demand reduction	AM reduces material and energy demand in prototyping and customized applications. Potential reduction in energy demand varies by sector, ranging from 4 to 27 percent.	Studies show sharing mobility can reduce GHG emissions by up to 50% by 2050	Production close to consumers and without combustion reduces wasted energy. Prosumers, who both produce and consume energy, may be more energy conscious also.
Existing and potential public policy instruments	Public support for R&I. AM included in industrial strategies. Yet, specific policies, including standards, are missing	Pricing /taxation schemes Subsidies on shared mobility Nudges and social movements	Subsidies. But many regulations hinder adoption
Concerns	Rebound effects, over-consumerism resulting from customization	Cyber security Finance in LMI countries	Financing in LMI countries, grid integration

[1] *Innovation stage: Research (fundamental science and technology exploration), Prototype, Demonstration, Early adoption, Market adoption and scale-up (Gallagher et al 2006).*

3. Three LED innovation case studies

For each of the three case studies, we summarize the context within which the innovation is emerging, its potential demand reduction, and the health of its innovation system functions. For more on the case study FIS analysis, please see SI1-3.

3.1 Case 1: Additive manufacturing (AM)

AM, or 3D printing, is a production method based on a process of joining materials to make objects from 3D model data, usually layer upon layer (Aboulkhair *et al* 2019). Plastics, nylon, metals, and ceramics can be used. Initially developed for rapid prototyping, AM could have great potential for larger-scale (rapid) manufacturing and, consequently, industrial energy demand reductions and associated emissions (see Table 1 and SI.1). Its biggest advantages are: (1) the manufacture of geometrically complex structures in a single-step process (Reis 2013); (2) major cost advantages in sectors where products need to be adapted to customers' needs (Aboulkhair *et al* 2019).

1. *Knowledge development:* maturity of AM varies greatly by sectors; in no sector is it applied for large-scale manufacturing (AMFG 2019). Universities are a main source of codified knowledge, but patenting is dominated by the private sector (Peña *et al* 2014). Innovation in new materials and methods for AM is progressing (Ngo *et al* 2018).

2. *Knowledge diffusion*: Collaboration among different actors required for large-scale application of AM (Lavoie and Addis 2018). (Ngo *et al* 2018).
3. *Guidance of search*: Many governments consider AM a technology of interest for industrial policy, but their strategies differ significantly, ranging from targeted public R&D funding (Samford *et al* 2017, McKinsey 2017)(Peña *et al* 2014) to fostering synergies with existing local industrial strengths (Samford *et al* 2017).(Samford *et al* 2017, McKinsey 2017)(Peña *et al* 2014)(Samford *et al* 2017)
4. *Resource mobilizatio*n: early-stage financing for AM innovation and funds for further development came both from private and public sources. (Peña *et al* 2014), including the automotive and aerospace, military, cement, and metal sectors (Vora and Sanyal 2020).
5. *Entrepreneurial activities*: private firms, mostly located in the US, were active in early technology development. Multiple major material manufacturers and key universities are engaging with AM technologies, establishing partnerships (McKinsey 2017).
6. *Market formation*: in 2017 the market for AM products and services was over $7 billion. (Thompson *et al* 2016). Yet, the penetration of AM technologies is estimated at only 8%, indicating untapped potential (Vora and Sanyal 2020). However, unit costs do not exhibit economies of scale, indicating limits to large-scale diffusion (Baumers *et al* 2017, Sculpteo 2014, Steenhuis and Pretorius 2017).
7. *Creation of legitimacy:* governments and the education sector generate legitimacy for AM technologies (e.g., inclusion of AM-relevant and specific training as part of undergraduate and graduate curricula) (Reis 2013). Yet, large-scale adoption of AM is inhibited by technical hurdles and lack of universal guidelines for metrology, inspection, and standardization, leading to concerns about IP protection and vulnerability to cyberattacks.

3.2 Case 2. Shared mobility (SM)

SM, characterized by asset sharing (e.g., a bicycle, e-scooter, vehicle) and facilitated by information technology (e.g., apps and the internet), holds promise for emission reduction and climate change mitigation (Creutzig *et al* 2022b). Four business models have been identified (Santos *et al* 2018): peer-to-peer platform (Ballús-Armet *et al* 2014); short-term rental managed and owned by a provider (Enoch and Taylor 2006, Schaefers *et al* 2016, Bardhi and Eckhardt 2012); Uber-like service (Wallsten 2015); and shared ride where private vehicles shared by passengers to a common destination (Shaheen and Cohen 2019, Liyanage *et al* 2019). Studies show that SM, mainly shared automated electric vehicles, cuts GHG emissions by one-third and 63%-82% per mile compared to a privately owned hybrid vehicle in 2030, 87%-94% lower than a privately owned, gasoline-powered vehicle in 2014 (Greenblatt and Saxena 2015). Berlin and Lisbon studies demonstrate that SM could reduce the number of cars by more than 90%, also saving valuable street space for human-scale activity (Bischoff and Maciejewski 2016, Martinez and Viegas 2017, Creutzig *et al* 2019, ITF 2016). The impacts depend on sharing levels –

concurrent or sequential – and the future modal split among public transit, automated electric vehicle fleets, and shared or pooled rides.

1. *Knowledge development*. SM-related services and technology have reached the developed stage (PBOT 2011, Zee 2016). However, improvement in service design and deeper integration of digitalization is needed (Creutzig *et al* 2019).
2. *Knowledge diffusion*. As users and shared mobility providers/business models interact, a reciprocal flow of insights occurs, shaping the design, functionality, and future iterations of shared mobility solutions (Ruhrort 2020). This iterative learning process, often referred to as "learning by using," nurtures innovation by incorporating direct user feedback into the R&D cycle (Hekkert *et al* 2007). Consequently, the network's role transcends traditional knowledge exchange to become a conduit for collaborative innovation, where the user's experience not only informs but actively shapes the direction of shared mobility evolution (Li 2023, Coretti Sanchez *et al* 2022).
3. *Guidance of search*. Private car ownership, fuel, and parking space taxation; shared mobility choice architecture and subsidies, and saving citizens useful time, particularly in big cities, raised awareness and motivated individuals to take up these LED services (Roca-Puigròs *et al* 2023, Weschke *et al* 2022). Using these strategies, service providers and inventors can customize their efforts to not only meet current needs but also predict and serve changing preferences and services. This promotes a more adaptable and customer-focused approach to developing shared mobility.
4. *Resource mobilization*. Both governments and the private sector (businesses) are investing in designing shared mobility infrastructure and services in various ways worldwide (Heinitz 2022).
5. *Entrepreneurial activities*. Sharing mobility has become widespread globally as an innovative service business model (Casprini *et al* 2019, Chaudhuri *et al* 2022, Ma *et al* 2018). Many small, medium, and big businesses actively invest in designing and providing services (Turoń 2022, Gilibert and Ribas 2019, Ma *et al* 2018).
6. *Market formation*. Markets are currently at the stage of scaling up, improving, and designing new services and also over space (Mouratidis 2022, Casprini *et al* 2019).
7. *Creation of legitimacy.* SM is already being adopted by individuals; however, social and data security improvement is key to more widespread adoption (Affia and Matulevičius 2022). Despite the vast potential for new business opportunities, authorities grapple with the challenge of effectively regulating and structuring SM and its associated data.

3.3 Case 3: Residential solar energy prosumers (SP)

Residential solar prosumers, who both consume and produce energy services (Rathnayaka *et al* 2012), have strong potential for energy savings because transmission losses are avoided and waste heat is not generated (Lee and Song 2021). In addition, awareness of energy use associated with

adopting solar can lead to energy saving behavioral changes. In large markets such as the US, Germany, and China, less than 5% of households have solar installed so the energy reduction potential of rooftop solar is an untapped resource (Denholm and Margolis 2008, Michaels and Parag 2016, Gagnon *et al* 2018) and the global potential is vast (Creutzig *et al* 2017, Haegel *et al* 2019). The global mitigation potential of solar energy is 2-7 GT CO2/year in 2030, among the highest of all mitigation options (Babiker *et al* 2022), with rooftops providing a substantial share. Technologies enabling solar prosumers are mature (O'Shaughnessy *et al* 2018a), the challenge being their integration in the grid, a form of infrastructure design. Therefore, social innovations and behavioral changes, especially peer effects, have a large role to play. The proliferation of household energy storage, either standalone or in electric vehicles, combined with digitalization, especially connectivity to the grid, would facilitate a larger role for solar prosumers (Denholm and Margolis 2016). This combination of development in social drivers and novel technical innovations is an important aspect within this innovation system.

1. *Knowledge development*. All technologies enabling solar prosumers are mature: solar panels, energy storage, electric vehicles, smart meters, and power systems (O'Shaughnessy *et al* 2018a). Grid integration at high levels of solar adoption has been demonstrated in some areas.
2. *Knowledge diffusion*: Components and know-how are widely available and transferring grid integration experience from areas with high solar adoption is now a focus (Heptonstall and Gross 2021).
3. *Guidance of search*: Public policy such as renewables obligations, subsidies, as well as information programs (like Solsmart in the US) raise awareness and orient expectations of growth. Solar is very popular (Hazboun and Boudet 2020, Roddis *et al* 2019).
4. *Resource mobilization*. Solar technologies benefit from massive investment globally, but a key issue is access to finance and investment in Low-to-Moderate Income (LMI) countries (Schmidt *et al* 2019).
5. *Entrepreneurial activities*. Small businesses play an active role, e.g. there are many small local installers in Germany (Neij *et al* 2017) and over 10,000 installers in the US (O'Shaughnessy *et al* 2018b). New business models, especially software, for managing and marketing power at local levels will be important as well providing finance in LMI countries (Egli *et al* 2022).
6. *Market formation*: Adoption has gone beyond early adopters to more mainstream consumers (Haegel *et al* 2019). Grid integration is key challenge as the share of prosumers increases. Market development depends on continued cost reductions, particularly in developing and LMI countries.
7. *Creation of legitimacy.* Market growth has conferred legitimacy, such that it is now part of the policy regime (Horstink *et al* 2021) although in some jurisdictions growth has stalled or has been thwarted by opposing actors . An inclusive governance approach to regulation and policies would help establish legitimacy. Peer-to-peer energy trading, the logical next

step for prosumers (Luo *et al* 2014), has not yet achieved legitimacy and strong political forces use extant regulations and natural monopolies to bar the inception of neighbors buying and selling electricity.

4. Unlocking LED Technological Innovations Pathways

To maximize their potential, LED innovation necessitates coordinated efforts from individuals, businesses, cities, regions and countries (also see SI.4) (Grubler *et al* 2018, Schot and Kanger 2018, Stern *et al* 2007). While a substantial focus is placed on the development and widespread adoption of new LED technologies, social aspects such as behaviors, lifestyle shifts, and more broadly the social dimension, are also vital components of LED solutions (Creutzig *et al* 2016, Niamir *et al* 2020a). By intertwining technological advancements with behavioral change efforts, LED pathways can lead to more effective and long-lasting results in mitigating climate change. While social dimensions are encompassed in FIS, here we explore them in greater depth. We discuss eight sets of key social enablers that can facilitate the scaling up technological innovation in support of LED, contingent on their distinct characteristics (also see Tables SI5.1-3):

1. ***Behavior and lifestyle changes*** play a pivotal role as enabler conditions in the transition to LED. By influencing individual and collective choices, these changes contribute significantly to shaping consumption patterns and reducing overall energy needs. As apparent from all three case studies, the successful development and deployment of technology in a LED scenario needs to go beyond the pure deployment of new technology and be accompanied by, and favor, meaningful change in individual behaviors and lifestyle.

2. ***Peer effects*** are central to accelerating innovation and spreading the adoption of LED solutions. Social and cultural processes play an important role in shaping what actions people take on climate mitigation, interacting with individual, structural, institutional and economic drivers (Thaler and Sunstein 2003).

3. ***Inclusive governance*** plays a crucial role in the deployment of LED innovations to achieve societal goals. Addressing climate change and improving human well-being requires an inclusive, equitable, and all-of-society approach. Multi-level governance and effective institutions can enable LED pathways by prioritizing inclusive decision-making, enhancing equitable access to finance, infrastructure and technology, setting targets and priorities, and mainstreaming climate actions across sectors and actors (Niamir and Pachauri 2023). This approach fosters collaboration and cooperation among government bodies, businesses, communities, and individuals, ultimately contributing to a more effective and holistic response to the challenges energy demand.

4. ***Infrastructure design and availability*** matter for effective LED measures since there are systematic interconnections between infrastructure design and practices (Cass *et al* 2018).

For example, in urban transport, infrastructure design and services provision contribute to higher uptake of LED options (Song *et al* 2017, Goodman *et al* 2014).

5. ***Finance and investment*** are crucial because LED measures tend to be capital intensive, i.e., they involve up-front costs and generate savings and benefits over time and require significant infrastructure to be successfully deployed. Therefore, access to finance is essential in adopting LED measures in low- and middle-income countries where the potential is very large but where access to capital remains a constraint (Egli *et al* 2022).

6. ***Market development and cost reductions*** can occur concurrently via learning effects. The granularity of many LED technologies makes them amenable to mass production and rapid learning. Social interactions, such as peer effects, can accelerate learning (Neij and Nemet 2022).

7. ***Regulations and policies*** are needed so that LED technologies are further developed and deployed in a sustainable way and in accordance with mitigation and other sustainable development goals. For example, under emissions regulation (Porter and Kramer 2006) are accessible to, and for scale-up LED innovations, and benefits all, not just the wealthy who could afford it early on, both within developed and extended to developing countries. They include investment in social innovations, behavioral and lifestyle changes through education, new norms, and mindsets.

8. ***Business models***. Business will need to part of the solutions, as business models will have to adapt to a new way of providing goods and services (Markard 2018, O'Shaughnessy *et al* 2020). Importantly, investment patterns will change. For example, the insurance industry might be affected by its role as an insurer of third-party liability.

4.1 LED Narratives

We offer illustrative LED narratives for the case studies of AM, SM and SP to highlight the crucial roles that the eight enablers can play in optimizing the potential of LED technological innovation. Because of the distinct characteristics of these cases, in addition to context and scale, all or only a few of these enablers may be applicable. Even though each case is at a different level of maturity, they are all at an early stage in their development relative to the level required to achieve 1.5C.

AM LED Narrative. By 2050 it is plausible that AM technologies will have significantly increased their penetration rate, but their potential to contribute to LED varies by sector: AM could reduce Total Primary Energy Supply (TPES) in aerospace fuels by between 9 and 35 percent, from aerospace manufacturing by between 8 and 19 percent and in the sectors of medical equipment and tools by between 5 to 19 percent, and 3 to 10 percent, respectively (Gebler *et al* 2014). Three critical junctures exist in the AM narratives. A first is whether the **technology** will mature and

proof-of-concept will be achieved for large-scale manufacturing. Achievement of proof-of-concept in several key areas—such as metal-based AM or AM based on recycled inputs—hinges on public support for innovation in the form of technology-push policies, including R&D investments and subsidies. Application of AM technologies in other sectors and their relevance for decarbonization is dependent on lifestyle changes and developing a culture of sufficiency which would avoid material and energy rebound. A second is whether new **business models** will be fostered to move away from traditional linear manufacturing and towards on-demand production. Network effects and changes in business models are necessary to promote the scale-up and give rise to learning-by-using dynamics, including increased technology efficiency and lower costs. Access to finance and investment needs to be granted to promote adoption among producers and service providers. A third is whether governance will promote the necessary **behavioral change**, mindsets, and targeted policies to ensure AM achieves deep emission reductions, circularity, and sufficiency as well as economic benefits. Tailored public policies, including regulation and the development of industry standards, are needed to promote a paradigm shift from linear and subtractive manufacturing to AM consistent with a deep sustainability transition.

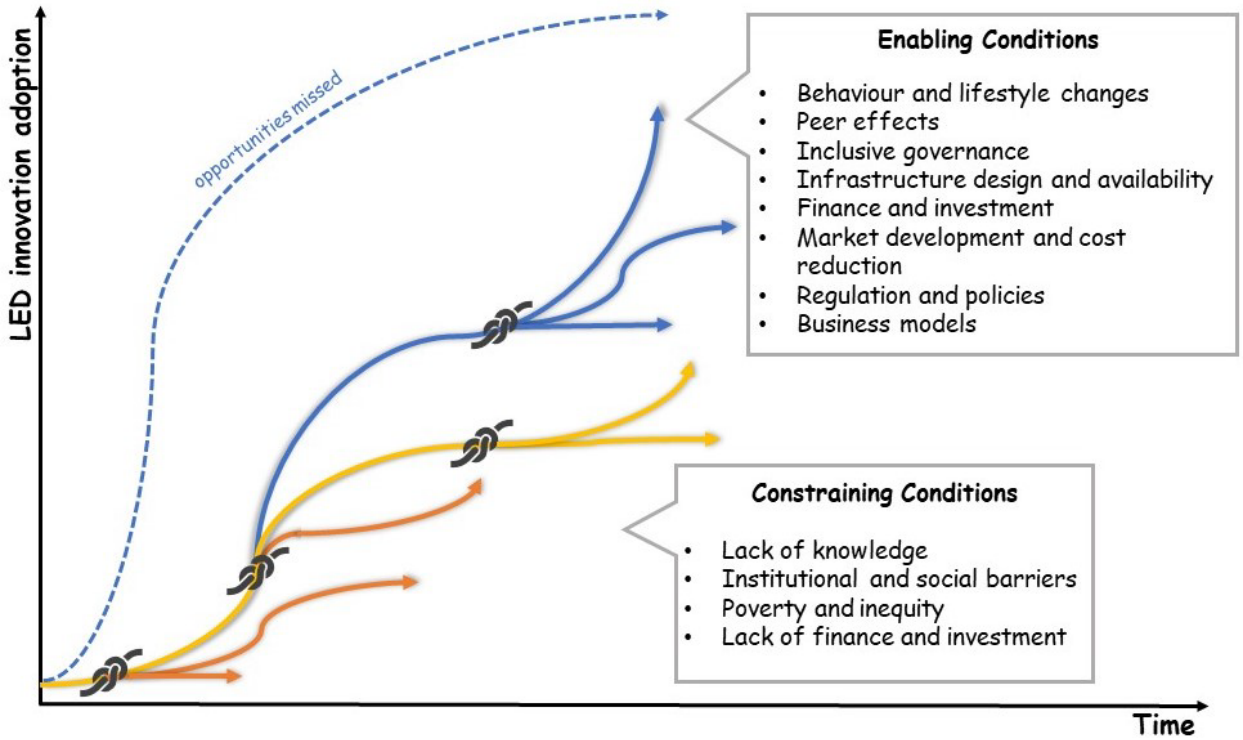

Figure 1: *Illustrative LED innovation pathways. Lines indicate the cumulative adoption of an LED innovation over time, with key junctures indicated by knots. Diverging LED innovation pathways (orange to blue) illustrate that interacting choices and actions by diverse actors—government, business, and civil society—can enable LED innovation adoption. Pathways and opportunities for action are shaped by the innovation stage, distinct characteristics, and previous actions (or inactions and opportunities missed) and enabling and constraining conditions. Social innovations can create enabling conditions allowing for steeper adoption pathways (blue pathways). At the same time, lack of knowledge, finance and investment, institutional and social drivers as well as*

poverty and inequity, halt the process (orange pathways). {illustrative pathways idea is adapted from IPCC AR6 SYR, Figure SPM.6 on sustainable development pathways}

SM LED Narrative. Shared mobility innovation demonstrates various levels of development and adoption linked to the economic, social, institutional, and financial contexts. For example, traditional micro-mobility like cycle rickshaws thrive in developing countries, while bike- and scooter-sharing systems flourish in developed countries. Drawing from the literature, several social enablers are relevant and have the potential to significantly influence the transition toward realizing the full LED innovation potential. Specifically, these enablers include **design and access to technology and infrastructure**, exemplified by carsharing's global expansion and shared electric vehicles' emission reductions (ITF 2017, 2019, 2020). Well-designed, safe and accessible infrastructure provides the necessary support to be effectively utilized and integrated, encouraging individuals and organizations to embrace and benefit from the advancements (Song *et al* 2017, Goodman *et al* 2014, Creutzig *et al* 2022b). **Policy packages** such as social and behavioral intervention, like nudges, can influence individuals' choices in favor of SM usage, e.g. "walk cycle ride" campaign (Rojas López and Wong 2017), while carbon pricing mechanisms can affect incentives (Richardson *et al* 2010, Eliasson and Mattsson 2006). **Social movements and peer effects** exist in that individuals are often motivated by collective sentiments and the behaviours of their peers when embracing new services and lifestyles (Burghard and Dütschke 2019, Whittle *et al* 2019). Another enabler, **business models**, includes expanding service offerings, fostering collaborative partnerships, and optimizing pricing, as well as **providing adequate finance and investment support** to ensures the development and expansion of SM infrastructure and services, making them more accessible and attractive to the public.

SP LED Narrative. Rooftop solar is mature and growing rapidly, but at less than 2% of global electricity supply, its future potential remains large, and the extent to which that potential is realized depends highly on social innovations and behavioral change in particular. Two key junctures in the rooftop PV narrative are 1) whether growth in adoption continues in existing markets, especially in East Asia, Europe, and North America, and 2) whether adoption proliferates in emerging low- and middle-income countries. If both occur, we will see rooftop PV take the upper pathway to reach well above 10% of the global electricity supply, perhaps accounting for half of all PV, which could account for half of electricity supply. That pathway depends on key social innovations. Existing market growth depends on governance and regulation, particularly supportive electric rate structures, credit for energy storage, and incentives for reducing demand and would be bolstered by the proliferation of peer-to-peer electricity trading, which itself requires modification of infrastructure design. The latter would give consumers more control and would take full advantage of the granularity that rooftop solar provides; peer effects combined with network effects could catalyze further adoption of rooftop solar. Emerging market growth depends on all the above, as well as a fundamental change in finance and investment, particularly credit access, which is central to improving costs and market development. Financing for rooftop solar remains much more expensive than in existing markets, which in combination with lower median

incomes, limits adoption. Business model innovations that can provide credit at rates like those in existing markets would help put rooftop solar on the upper pathway. One can also imagine a scenario where none of these supporting social innovations take hold, and adoption grows at a rate that only grows with overall demand leaving its share unchanged. While many middle pathways exist, an especially problematic one has supporting social innovations take hold in both existing and emerging markets, but access to finance remains a constraint in emerging markets. That would lead to a tremendous, wasted opportunity both for the global impact and distribution of the access to benefits that rooftop solar can provide.

5. Conclusion and directions for further work

This paper examines three pertinent innovations in LED through the lens of the FIS framework: additive manufacturing, shared mobility, and solar prosumers. Furthermore, it discusses key enablers to unlock their LED potential and demonstrates ways for scaling them up to widespread adoption. We highlight that technological innovation is not the sole driver of LED. Rather, realistically achieving LED requires a range of crucial non-technological, non-cost aspects of technology diffusion, such as changing behaviors, social norms, and governance, all in the context of heterogeneous agents and the development of local knowledge. Consequently, this study underscores the need for additional bottom-up qualitative and quantitative research and analysis. This approach can offer a more in-depth understanding of the complexities and, potentially, serve as a valuable complement to addressing the challenges posed by large-scale IAMs.

To present feasible LED scenarios, capture key enablers and explore (non-linear) solutions, current scenario modelling needs three key shifts. First, large-scale IAMs and energy system models could be complemented with modelling approaches which can more realistically capture heterogeneous effects and the role of peer effects in technology development and diffusion. This is the case, for instance, for agent-based modelling, which has the potential to play an increasing role in informing large-scale modelling exercises (Niamir *et al* 2020a, Edelenbosch *et al* 2022). Second, the key role of non-technological drivers in LED innovation points to the importance to develop more detailed LED narratives to ground and justify model results—that is, provide rationales for specific model constraints to account for changes in lifestyle, norms, and beliefs. Finally, available IAMs are extremely limited in their ability to depict different policy instruments and mixes. This surely represents an interesting area of further model development and is a particularly important one in the context of LED pathways.

To improve our understanding of LED innovation and narratives alongside our modelling tools, there are two complementary fruitful avenues of future work. On the one hand, detailed empirical data and analysis on LED innovation development and adoption, particularly in LMI countries, is needed to characterize the intersections between institutional, political, environmental, social, and economic factors which contribute to LED innovation development and adoption at different scales in different geographies (Beckage *et al* 2020, Rubiano Rivadeneira and Carton 2022). On

the other hand, future research should inform and complement IAMs by distilling specific insights regarding policy instrument and mixes in support of LED innovation. This includes valuable insights on establishing and promoting policy motivations, addressing innovation system failures, improving technologies and services, facilitating behavioral change and LED innovation adoption, enabling new business models, and addressing adverse consequences of successful adoption—e.g., material or energy rebound or distributional repercussions. Attention should be given to the role of local context both in adoption and policy, especially in LMI countries and to the combination, timing and strategic sequencing of policy instruments. Pursuing this comprehensive research agenda can help unlock the potential of LED scenarios in the context of urgent deep decarbonization.

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Working paper

The 'High-with-Low' Scenario Narrative: Key Themes, Cross-Cutting Linkages, and Implications for Modelling

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WP-23-009

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Abstract

We define a global ‘High-with-Low’ scenario that delivers high wellbeing with low energy and material resource consumption while limiting global warming in line with Paris Agreement targets. The High-with-Low scenario comprises a rich thematic narrative and a quantitative framework for interpreting the narrative using systems and sectoral modelling tools at different scales. The three central themes of the High-with-Low scenario are decent living standards for all, innovation and granularity, and digitalization. Inter-linkages between these themes emphasize drivers of change towards a High-with-Low future that include decentralization, adaptability to local needs, accelerated diffusion through peer and network effects, and the management of complexity on shared infrastructures. However, the direction of change is not deterministic. The High-with-Low scenario envisages a set of specific and strong governance institutions for coordinating a highly distributed global sustainability transition. To help develop and enrich these narrative aspects, we also set out some guidelines and parameterisations for quantitative model interpretations of the High-with-Low scenario. 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. In particular, we emphasize the overall development pattern of the High-with-Low scenario as one of conditional convergence in which energy services for well-being increase substantially in the Global South catching up to levels maintained in the Global North, while associated resource use tends to converge, combining a contraction in the Global North with relatively modest increases in the Global South.

Acronyms

DLS	Decent Living Standards
HwL	High-with-Low
LED	Low Energy Demand

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The High-with-Low scenario

Key concepts & terms

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 rapid absolute reductions in resource use and GHG emissions.

Our scenario achieves high levels of human wellbeing that are more equitably distributed globally with significantly 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**' (HwL) 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 footprints within planetary boundaries (Rockstrom, Steffen et al. 2009, Rockström, Beringer et al. 2021, Fanning, O'Neill et al. 2022).

Our interpretation of sustainable development broadly follows the framework developed by Matson, Clark et al. (2016): "*Sustainable development aims to provide inclusive wellbeing, while increasing development capital and respecting planetary boundaries."*[1] The focus on **well-being** recognizes both tangible and intangible constituents across material as well as social dimensions, both individual (health, education, opportunity) as well as collective (community, security). The term "inclusive" means wellbeing should be universal, i.e. achieved for all.

Services are another key concept in our High-with-Low (HwL) scenario narrative. Services refer to the amenities or functionalities like comfort, mobility, or social interactions that constitute well-being (Kalt, Wiedenhofer et al. 2019). Resource or economic inputs like income, energy, or materials (both as flows and stocks embodied in infrastructure) are 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) (Haberl, Wiedenhofer et al. 2017, Lamb and Steinberger 2017).

[1] 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 & 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, partially complementary, and non-substitutable or with substitutability constrained by planetary boundaries and minimum requirements to safeguard ecosystem services (Rockstrom 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 and socio-metabolic resource use is organized in a more circular and efficient manner. For example, copper extraction for electric and digital infrastructure is feasible 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.

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 resource inputs; the relationship can be improved by increasing service efficiency. Second, focusing on services as 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 metres 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.

Positioning High-with-Low within the scenario literature

The High-with-Low (HwL) scenario is a development and enrichment of the global Low Energy Demand (LED) scenario (Grubler, Wilson et al. 2018). LED significantly pushed down the lower bound of energy consumption explored within global scenarios and modelling studies limiting warming to 1.5°C. Global final energy in LED by 2050 is 245 EJ, compared to median values of 442 to 544 EJ in 1.5°C scenarios with medium to high energy demand (Scott, Smith et al. 2022).

LED also helped establish demand-side transformation as an entry point for climate mitigation with stronger co-benefits than more conventional supply-side strategies, and significantly reduced reliance on carbon dioxide removal as a mitigation strategy. This perspective is not without its detractors: LED's emphasis on absolute demand reductions has been critiqued as a 'Goldilocks' future that improves living standards in the Global South without acknowledging the need for resource-intensive industrial and economic development (Semieniuk, Taylor et al. 2021). Energy demand reductions also meant LED was characterised as having low social and institutionally feasibility within recent multi-criteria feasibility assessments of mitigation scenarios (Brutschin, Pianta et al. 2021).

As an alternative long-term scenario paradigm, LED has been used as a reference scenario or illustrative mitigation pathway in IPCC reports including the Special Report on Global Warming of 1.5°C (Rogelj, Shindell et al. 2018) and the Sixth Assessment Report[2] (Riahi, Schaeffer et al. 2022). LED-type narratives have also been interpreted in national scenario modelling studies including in France and the UK (négaWatt 2017, Barrett, Pye et al. 2022).

The HwL scenario narrative's emphasis on providing high levels of wellbeing while minimizing resource use follows the tradition of efficiency scenarios that focus on service delivery through radically improved technological, institutional and social provisioning systems. These were first introduced as 'soft' development paths by Amory Lovins back in 1976 (Lovins 1976). Subsequent studies further developed efficiency pathways within a wider set of scenarios including the 'C' scenarios of the World Energy Council (Nakicenovic, Grubler et al. 1998), the 'B1' scenarios of the IPCC Special Report on Emissions Scenarios (Nakicenovic, Alcamo et al. 2000), and the 'Efficiency' scenarios of the Global Energy Assessment (Johansson, Nakicenovic et al. 2012).

[2] P1 in the Special Report on 1.5°C, and IMP-LD (Illustrative Mitigation Pathway – Low Demand) in the Sixth Assessment Report.

Importantly, however, the current SSP (shared socioeconomic pathways) framework used in the IPCC and other contexts (O'Neill, Kriegler et al. 2016) does not represent soft or efficiency pathways nor associated policy strategies. This omission triggered the development of LED, and now HwL, as a necessary contrasting perspective to broaden out the future possibility space explored by long-term scenario thinking. As such, the HwL narrative should not be misinterpreted as simply another incarnation of the 'green growth' SSP1 scenario as its narrative elements are quite different, relying not on enlightened environmentalism and shifting values, but on bottom-up drivers of development and living standards.

HwL should also not be interpreted as a narrative for an (economic) **degrowth** scenario (Victor 2012, Kallis 2017). HwL intentionally makes no reference to classical economic scenario variables such as GDP as these cannot adequately capture many salient elements of HwL (e.g., wellbeing, social innovation, lifestyle changes, novel forms of service provisioning operating outside classical commodity markets). Additionally, while resource inputs in HwL are drastically decoupled from service levels globally, in the Global North service levels (i.e., outputs) remain high or even slightly increase, but they grow substantially in the Global South. This is contrast to the principles underlying current "degrowth" debates (Hickel, Kallis et al. 2022).

Energy and **materials** are the principal natural resources considered in the HwL scenario and in the LED study, but – as the LED name suggests - with greater emphasis on energy in the quantitative interpretation using MESSAGE, an energy systems-based integrated assessment modelling framework (Grubler, Wilson et al. 2018). This is not to downplay the importance of the **material** dimensions to low resource futures. Industrial output accounts for around one quarter of global GHGs through the processing of materials into products, stocks, and infrastructures which in turn shape and lock-in future energy needs (Hertwich 2021, Lamb, Wiedmann et al. 2021). Other **material** stock-flow modelling analyzes provide complementary insights to LED on the material implications of climate change mitigation pathways (Krausmann, Wiedenhofer et al. 2020), including those that explicitly interpret the LED scenario through a material lens (Fishman, Heeren et al. 2021, Pauliuk, Heeren et al. 2021). Additional complementary studies have also elaborated on the material and infrastructure needs for decent living standards worldwide (Fisch-Romito 2021).

Studies focused more explicitly on the material dimensions to low resource futures draw on circular economy concepts to 'narrow, slow, and close' material loops through better design, lightweighting, and dematerialization (narrow), extending product durability and longevity (slow), refurbishment and recycling (close) (Bocken, de Pauw et al. 2016). In general, circular economy strategies reduce both raw material and energy resource use, but not in all cases (Hertwich, Ali et al. 2019, Cantzler, Creutzig et al. 2020). The 'narrow, slow, close' taxonomy for material-focused mitigation strategies are aligned with the transformative approach to planetary socio-metabolism represented in HwL with its emphasis on service efficiency and dematerialization alongside step change efficiency improvements in resource use within service provisioning systems.

Central themes of the High-with-Low scenario

The global LED study that provides the start point for this High-with-Low scenario emphasized five 'mega-trends' shaping energy system development to 2050: urbanization; new forms of energy service provision; user-oriented innovation, particularly through ICTs; diversification of end-user roles; improving quality of life

(Grubler, Wilson et al. 2018). The global LED scenario also centerd around five more specific drivers of change: rapid transformation; decentralized service provision; granularity; digitalization of daily life; and a shift from owning to accessing.

In the High-with-Low (HwL) scenario narrative, we extend and enrich the global LED study in three important ways. First, we expand on the importance of three underpinning and inter-related themes: **decent living**, **innovation**, and **digitalization**. Each of these themes has a strong connection to the global LED scenario, and have seen significant progress in both practice and research in recent years – as examples: decent living in the SDG agenda; innovation in the exponential cost declines observed in solar PV, batteries, and electronics; and digitalization through pandemic experiences of service provision rapidly shifted online. We also show and discuss how these three themes inter-link in synergistic ways to ensure a resource-efficient future with high and inclusive wellbeing (Figure 1).

Second, we more explicitly consider the policy, **governance**, and coordination challenges associated with delivering High-with-Low transformational change while mitigating risks and adverse impacts of a highly distributed program of social, technological, and behavioral solutions.

Third, the global LED scenario and modelling – in common with most of the mitigation pathway literature – analyzes technological change in more detail than **social and institutional change**, despite their inseparability in practice. Here, we try and expand as much as possible on the social, behavioral, and organizational implications of a High-with-Low future.

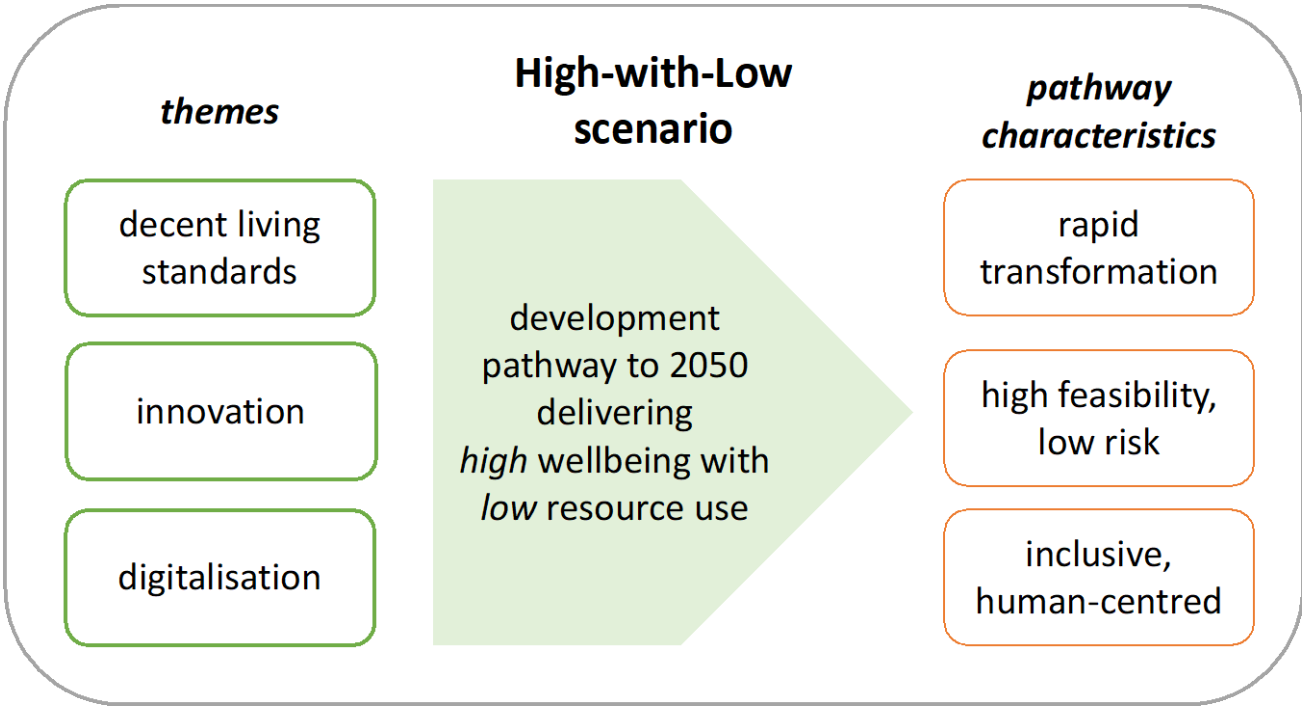

Figure 1. Three main themes in the High-with-Low scenario, and characteristics of the resulting development pathway to 2050.

Decent living for all

First and foremost, the High-with-Low scenario describes a more equitable, fair, and inclusive future, 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, SEforALL 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 Rozenberg 2017, Hallegatte, Fay et al. 2018, Bastia and Skeldon 2020).

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*". Importantly, DLS constitutes a minimum threshold or floor to consumption that is required for ensuring human wellbeing for all.

This is distinct from the idea of a consumption corridor defined by both a minimum and maximum threshold to consumption or sufficiency (Di Giulio and Fuchs 2014, Lamb and Steinberger 2017, Fuchs, Sahakian et al. 2021). Despite renewed attention on and importance of **sufficiency** (see Box 1), the High-with-Low scenario does not define any maximum thresholds or ceilings. This is also because how to quantify such a sufficiency ceiling remains contested and existing examples are limited and very context specific to date.

The DLS framework identifies groups of basic needs 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 and improving human wellbeing (Brand-Correa and Steinberger 2017, Haberl, Wiedenhofer et al. 2017, Lamb and Steinberger 2017, Creutzig, Niamir et al. 2021, Gillingham, Huang et al. 2021). 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 (Plank, Liehr et al. 2021), how social norms and cultures shape use, and whether associated waste and emission streams from socio-metabolic systems impact human and planetary health (Pauliuk and Hertwich 2015, Haberl, Wiedenhofer et al. 2019) (Figure 2).

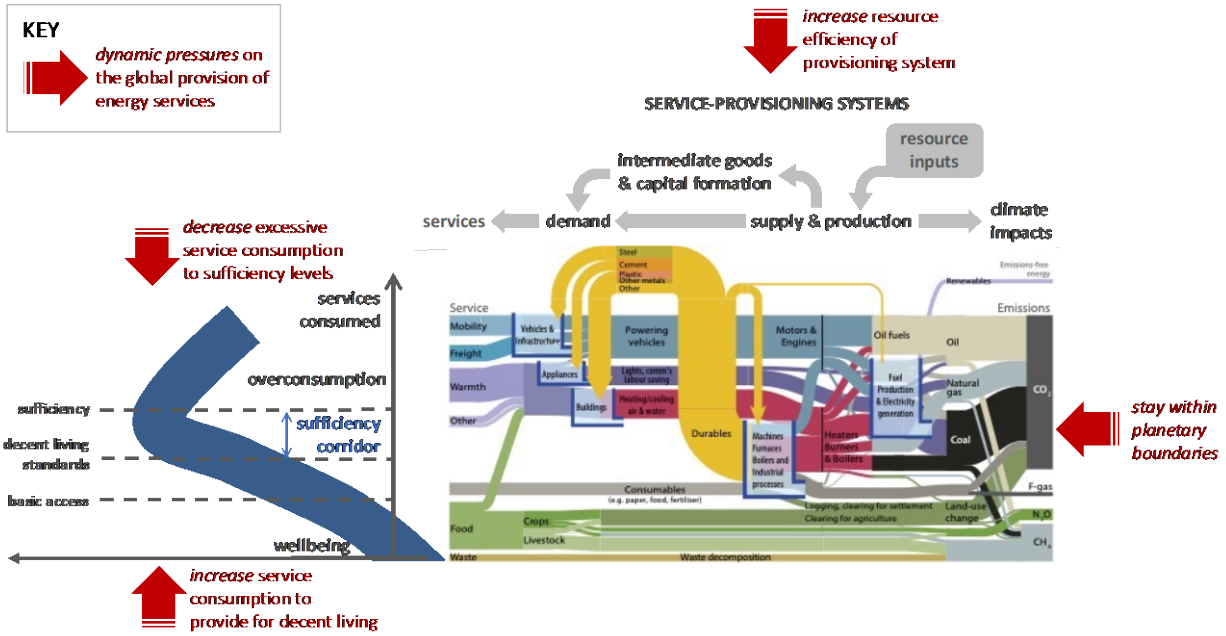

Figure 2. Transforming how services are provided to meet human needs with fewer resource inputs. Left panel shows stylized relationship between levels of service provision and human wellbeing. Right panel shows the resource processing flows (Sankey diagram) through the global service provisioning system using data for 2010, from Bajželj, Allwood, and Cullen (2013). Thick red arrows show dynamic pressures to deliver High-with-Low outcomes. Source: Wilson, Grubler et al. (2023) based on TWI2050 (2020).

BOX 1. The importance of sufficiency: Defining floors and ceilings.

Sufficiency in Latin means “enough”. The concept has been in focus recently in discussions of ways to transform our societies to sustainable and low-carbon futures (Burke 2020, Defila and Di Giulio 2020, Akenji, Bengtsson et al. 2021, Fuchs, Sahakian et al. 2021). Sufficiency is clearly normative in that it targets both under- and over-consumption, and so focuses on defining lower and upper consumption thresholds that both achieve human wellbeing in an equitable manner and within environmental and planetary limits. It builds on recent work on how to define and quantify a floor or minimum threshold of material needs necessary for human wellbeing (Rao and Min 2017, Rao, Min et al. 2019, Kikstra, Mastrucci et al. 2021), and growing evidence that ever-increasing consumption does not bring ever higher levels of happiness or wellbeing and threatens the health of the planet and global ecosystems (Wiedmann, Lenzen et al. 2020, Rao and Wilson 2022).

While there have been advances in defining and measuring a floor or minimum threshold to consumption that is universally applicable, efforts to define and quantify a ceiling or maximum threshold have so far been very limited and context specific. An early practical example of defining a sufficiency ceiling for consumption is the 2000-Watt Society initiative in Switzerland (Spreng 2005). More recently, the French Negawatt association has combined the three pillars of sufficiency for avoided consumption or demand, efficiency for reduced material and energy intensities, and renewables for decarbonization to develop an energy transition scenario for France (négaWatt 2017).

Despite recent conceptual and scientific advances in how to define and measure sufficiency, much remains to be answered in how to specify and quantify limits of consumption. Importantly, increased understanding of underlying drivers of overconsumption is also needed to overcome opposition to and increase acceptance of ‘sufficiency’ lifestyles.

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. New resource-efficient technology enabled by digitalization and providing new services amidst changing end user roles has to play a central role.

Consequently, a central feature of the High-with-Low scenario is that innovation must accelerate and must be directed or governed. 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 resource-efficient 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 resource-efficient innovation in the HwL scenario also make it amenable to acceleration (Box 2). Solutions tend to be smaller scale, more distributed, and more modular - what we call 'granular' (Wilson, Grubler et al. 2020). Examples include: building insulation, , non-motorized and shared mobility schemes, dietary changes, efficient appliances, distributed supply and storage technologies like PV panels, fuel cells, and batteries.

Smaller scale technologies show both faster learning (Sweerts, Detz et al. 2020) and more rapid diffusion (Wilson, Grubler et al. 2020). In addition, the emergence of digitalization as a general purpose technology provides an array of new possibilities across service provisioning systems linked to DLS (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 solutions combine scalability with customization, so can better serve the rising demands for decent living that the High-with-Low scenario implies.

Box 2. 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 catalyze 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 include lower adoption risk and more flexibility (Wilson, Grubler et al. 2020), especially with many heterogeneous adopters and of particular importance in DLS adoption contexts.

Many iterations. Technologies and behaviors 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).

All of these changes require a strong role for governance in guiding the direction of innovation toward HwL outcomes, as well providing infrastructural support (Nemet and Greene 2022). Social and business model innovation, typically in combination with hardware and digital innovation, is central to the High-with-Low scenario 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 High-with-Low scenario. High-with-Low therefore sees the widespread adoption of existing resource-efficient practices, broadening to new geographies and new users, as well as novel combinations of behavior, technology, and business models. Box 3 provides some illustrative examples.

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. A salient interpretation of the innovation history since the onset of the Industrial Revolution points to the critical interplay between innovations in hardware on the one side and software and orgware on the other (Grubler, 1998). Institutional, social, and economic settings provide the environment and incentives in which hardware innovations can be developed. They are also critical in governing the adoption of innovations and for ensuring associated learning and experimentation. Innovation agents (producers and users) do not operate in a vacuum, but in social, economic and institutional contexts that influence their behavior and interactions. In turn, cross-cutting innovations such as digitalization can drastically change the way innovation agents act and interact, enabling improved coordination and accelerating collective learning processes that are key to a rapid sustainability transition.

Box 3. Examples of intertwined technological and social innovations in the High-with-Low scenario.

Combinations of social, behavioral, business-model, and technological innovations have the potential to deliver HwL outcomes (Niamir, Verdolini et al. 2023). Three illustrative examples are:

Additive manufacturing. Also known as 3D printing, this term refers to a range of manufacturing methods where metallic, ceramic, or plastic objects are fabricated using a computer-based design and typically applied in layers of material. They have the potential to deliver customized products with reduced shipping energy and less material.

Shared mobility. Here mobility services are provided by means of a shared asset (e.g., a bicycle, e-scooter, vehicle) combined with the use of hardware devices and software to connect users and providers. It was the potential to reduce both energy and material demand.

Solar prosumers. These households both consume and produce energy services and consequently have strong potential to reduce energy demand because transmission losses are avoided and waste heat is not generated.

In all cases, there is strong potential for widespread adoption of these approaches, subject to a set of eight social enablers or conditions needed to unlock innovation pathways: behavior and lifestyle changes; peer effects; inclusive governance; infrastructure design and availability; finance and investment; market development and cost reductions; regulations and policies; and novel business models (Niamir, Verdolini et al. 2023).

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 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 (Box 4). 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) (Royal Society 2020, Wilson, Kerr et al. 2020, Creutzig, Roy et al. 2022). The co-design of digital transformation and sustainable development strategies is essential for steering the rapid ongoing digitalization of social and economic processes towards High-with-Low goals (Digitalization for Sustainability (D4S) 2022, Pauliuk, Koslowski et al. 2022).

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 additional benefits of rapid innovation cycles through experimenting, testing, learning, and improving that are associated with both digital and granular technologies. Data-rich systems for providing or improving shelter, nutrition, health, socialization, and mobility allow for greater differentiation of services to provide DLS 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 HwL solutions and policies work. (See also Box 4).

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.

Box 4. Examples of High-with-Low solutions dependent on, or enabled by, 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 maximize system efficiencies and occupancy rates (ITF 2017). This also requires clear governance approaches to co-design technologies (e.g., vehicles), infrastructures (e.g., public transit systems), market incentives and regulation.

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).

Health, work and leisure. Teleworking, teleconferencing, and virtualization of health and education services (all spurred by the pandemic) offer substitutes for energy-intensive travel.

Consumer goods. Dematerialization through 'functional convergence' of multiple services and applications onto single digital devices (phones, tablets, laptops) acting as gateways to cloud-based service provision (Ryen, Babbitt et al. 2015, WEF 2019).

Thermal comfort. Smart home technologies and home energy management systems configured to optimize heating and cooling for domestic comfort, maximize 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).

Logistics. Data-rich optimization of intra-urban logistics operations for products, deliveries, mail, food and waste can help improve overall system efficiencies and reduce resource demands.

Cross-cutting linkages between themes

The three themes central to the High-with-Low scenario interact to generate a number of cross-cutting linkages (Figure 3). In a High-with-Low future, these linkages are synergistic and supportive of resource-efficient outcomes and inclusive wellbeing. However, these outcomes are not deterministic, and indeed, the center of Figure 3 emphasizes the importance of coordination and governance in achieving the High-with-Low scenario. The same cross-cutting linkages in the absence of strong governance institutions could generate inequalities, exclusion, extractive resource dependence, and trade-offs between SDGs.

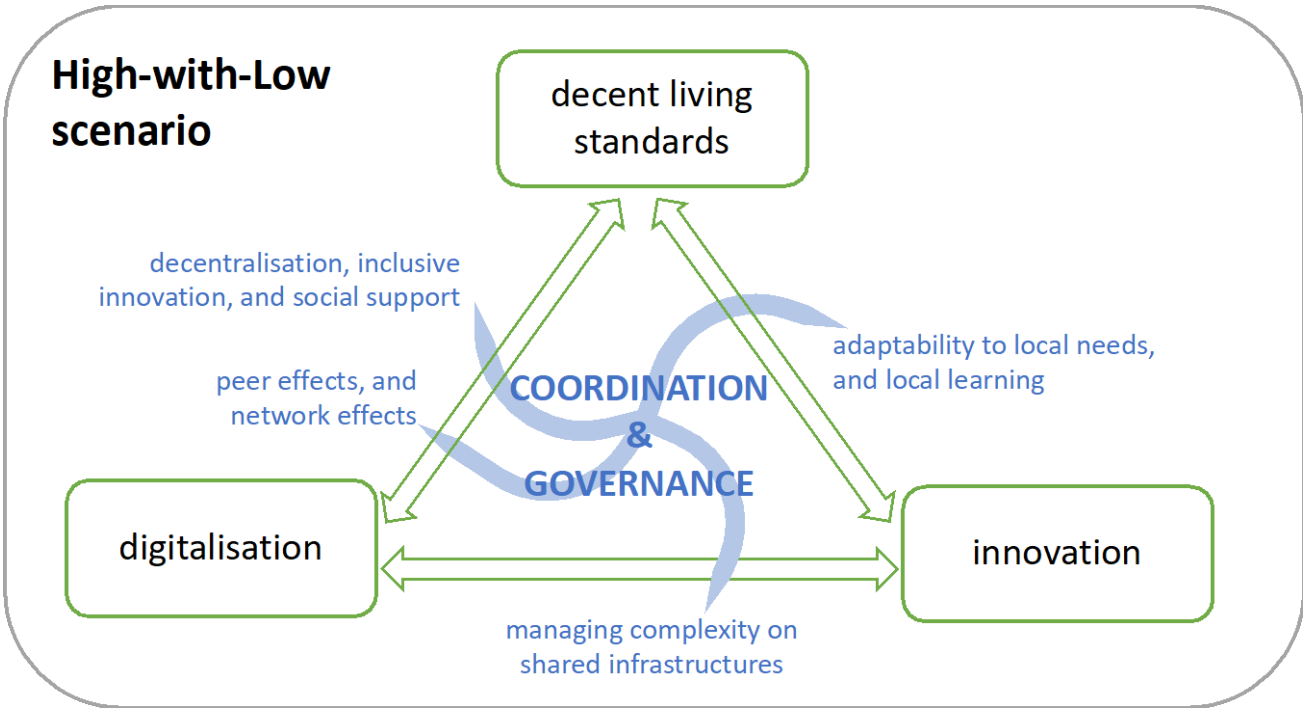

Figure 3. Cross-cutting linkages between the three central themes of the high-with-low scenario.

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 aspire 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 framing of the future, 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 a tendency 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 (Brand, Muraca et al. 2021). High-with-Low innovation includes that which originates from, and operates in, civil society. This is more localized, context specific, and socially determined (Vogel, Steinberger et al. 2021). 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 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). A specific example is how mobile phones are used 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 (Box 5).

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).

Box 5. 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.[3]

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

HwL solutions tend to be demand-focused, human-scaled, and granular. As noted earlier, smaller unit scales enable rapid experimentation and learning, as well as adaptation possibilities for diverse market and social conditions. 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 in High-with-Low is the reorientation of local learning to the diverse set of needs around supporting DLS. This 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). This enhances their social legitimacy and acceptance, supporting accelerated diffusion. 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), consumers' engagement (prosumers), or innovative financing opportunities (cooperatives or crowd funding schemes). These examples highlight again the intertwined social, technological, and business model characteristics of High-with-Low.

Peer effects, and network effects

Realizing the potential of HwL innovations 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 HwL 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

[3] https://stories.cgtneurope.tv/hubs/innovation-action-change/can-technology-end-poverty/index.html

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 HwL 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 HwL 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). 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 HwL innovation by increasing the appeal of HwL behaviors and systems over time. Digitalization provides the driver for connectivity and interoperability to enhance the value of HwL as it attains scale and more users (Kubli and Ulli-Beer 2016). For example, aggregating systems to the scale of smart cities where "connected intelligence" underlies many aspects of daily life creates increases adoption of HwL behaviors as more people engage with the system (Komninos 2019). The value of peer to peer energy trading among households also 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). Physical infrastructures enabling the HwL scenario apply particularly to digitalization (e.g., universal fast broadband access), sharing economies (e.g. urban pooled vehicle fleets), and renewable electrification (e.g., transmission and distribution networks). Of these three infrastructures, the clean energy transition requires a large expansion of infrastructure with associated material needs (Hertwich 2021, IEA 2021).

In addition to these infrastructure requirements, a cross-cutting theme within the HwL scenario is how these infrastructures are used. In particular, innovation and digitalization combine to enable the balancing and managing of increasingly complex resource flows (e.g., electricity networks) and the effective use of shared infrastructure (e.g., transportation).

First, digitalization 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) (Royal Society 2020). Digitalization also enables more resource-efficient design of products and infrastructures including through the tracing of material contents (e.g., building information modelling and building passports) in the wide context of secondary materials management in a more circular economy (Hedberg and Šipka 2021, Material Economics 2022).

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 optimized to deliver intra-urban mobility requires only 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). Strong governance institutions are needed to coordinate the activity of competing digital providers so as not to undermine public purpose aims.

Quantitative modelling of the High-with-Low scenario

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 modelling tools will further enrich understanding of policy levers, outcomes, distributional effects, and pathways over time.

Relevant models for High-with-Low analysis will track energy, material, land and other resources converted through service provisioning systems into useful final services. This quantitative step invites modelers to select inputs, parameters, constraints, and model processes that are consistent with the High-with-Low scenario narrative, and that generate change dynamics and outcomes also consistent with the High-with-Low scenario. At their most general, these HwL outcomes must include: (1) decent living standards for all; (2) global warming limited to 1.5°C without large-scale CDR; (3) absolute reductions in the use of resources.[4]

[4] Global warming outcomes estimated or modelled from long-term carbon budgets are possible in global IAMs with comprehensive coverage of energy and land-use emissions. Other models, including national or sectoral models, should

This leaves considerable interpretative freedom that means HwL scenario modelling 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 modelling the High-with-Low scenario, here we set out certain guidelines that provide entry points, boundary conditions, and recommendations for supporting modelling efforts.

We start by focusing on the central dynamic of the HwL scenario: rising activity levels for universal DLS, alongside strong structural change[5] towards new forms of service provision (with associated changes in technologies, energy carriers, and infrastructures involved in service provisioning systems). We then provide quantitative insights on the achievement of decent living standards for all (as modelling outputs consistent with the HwL scenario), and finally on peer effects and digital innovations (as modelling processes and inputs consistent with the HwL scenario).

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 framework also explicitly considers the demand for materials and its corresponding energy use with a combined decompositional approach combining materials intensity with energy intensity following the methodology established for the original LED scenario but with improved and revised input/output data. 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 (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

aim for consistency with appropriately downscaled or sector-specific 1.5°C pathways, illustrated by the global LED scenario.

[5] Note the alternative economic definition of structural change referring from the transition from primary to secondary to tertiary production (e.g., agriculture to manufacturing to services).

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).

The overall development pattern of the HwL scenario is therefore one of conditional convergence in which energy services for well-being increase substantially in the Global South catching up to levels maintained in the Global North, while associated resource use tends to converge, combining a contraction in the Global North with relatively modest increases in the Global South.

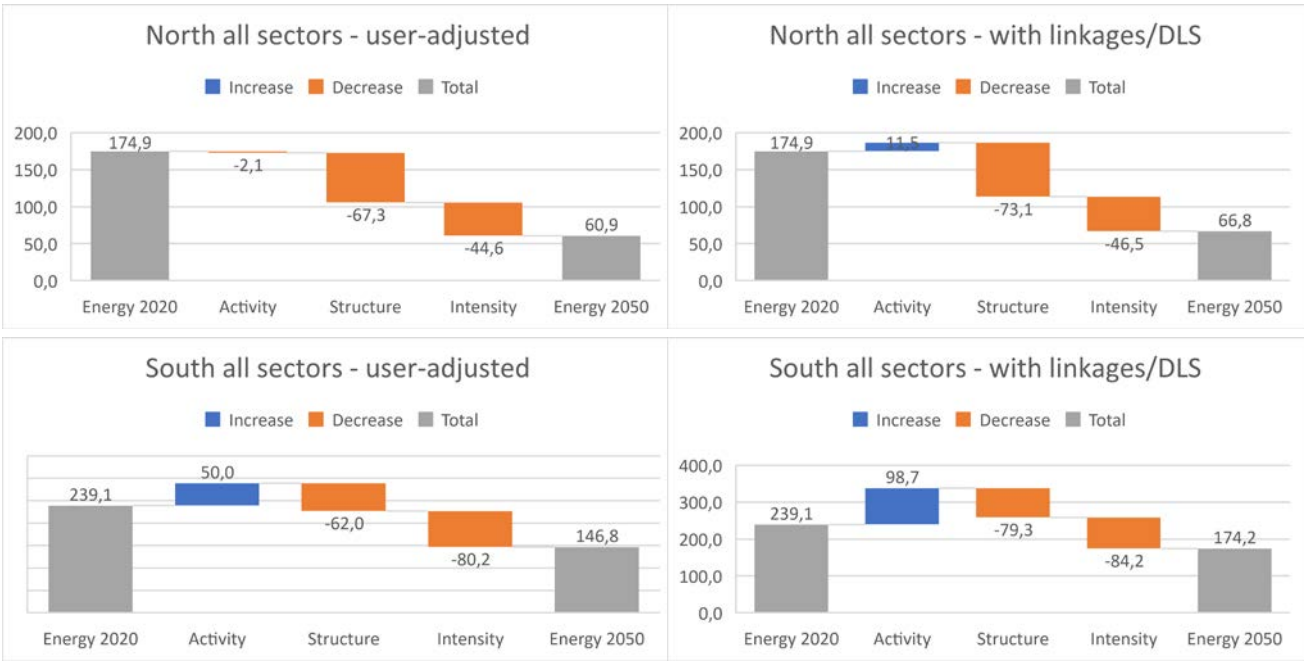

Figure 4. Changes in final energy use from 2020 to 2050 decomposed into activity, structure, and intensity components in a High-with-Low scenario, distinguishing: (1) Global North (upper panels) and Global South (lower panels); (2) user-adjusted global LED scenario (left panels) and inter-sectoral linkages and DLS scenario (right panels). All units in EJ/yr.

For HwL scenario modelling studies with different regional disaggregations (compared to the two region Global North – Global South results shown in Figure 4), we provide the following recommendations:

- Use the DETRAS accounting framework and modify the data with your own region/scenario values for 2020 and 2050.
- Compare the decomposition factors in your scenario to that for global HwL 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 HwL scenario (Figure 4).

Ensuring High-with-Low modelling is consistent with activity levels and energy requirements to provide decent living standards for all

Modelling the High-with-Low scenario can draw on and benefit from extensive quantitative assessments of decent living standards (DLS). Table 1 makes explicit the underlying assumptions on activity levels and energy intensities assumed for meeting each dimension or component of DLS. Table 2 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 DLS-achievement 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, e-education). Consequently there may be further potential to narrow these gaps in a dynamic sense through additional changes in service provisioning systems that affect the pace and extent of improvement in energy and material intensities over time.

The data in Table 1 and Table 2 provide benchmarks against which HwL modelling 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. These can be substantial. In addition, alternative service provisioning (e.g. shared mobility as opposed to privately owned vehicles) can also substantially lower service costs and so 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).

The material dimensions to DLS achievement are not currently as well defined, but are being actively explored. One recent study quantified the material stocks (infrastructure requirements) for delivering mobility services in 172 countries in 2021, and assessed empirical relationships against the mobility dimension of decent living, finding diminishing returns to wellbeing above levels of 92 – 207 t/capita of mobility infrastructure (Virág, Wiedenhofer et al. 2022).

Table 1. 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 2. Energy gaps for providing five dimensions of DLS for all in eleven world regions. Adapted from: (Kikstra, Mastrucci et al. 2021).

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

Modelling tools used to explore High-with-Low futures will generally have weak or no representations of the peer effects, network effects, and customization potentials for HwL strategies at the intersection between decent living, innovation, and digitalization (see Appendices for examples of modelling approaches).
Peer effects, network effects, and customization are essential for accelerating improvement and adoption of resource-efficient technologies as they interact to generate non-linear effects.[6] 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. While this outcome emerges from a largely stochastic process, we can use observed effects, for example that each additional residential solar installation in a neighborhood increases the likelihood of additional adoption by 0.8 percentage points (Bollinger and Gillingham 2012).
- *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.

[6] 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.

- *Customization*. The potentially important role for local adaptation and customized implementation of generic components implies that more differentiation of HwL strategies will be needed. Customized solutions are highly amenable to learning-by-doing and thus their costs and adoption should be endogenous and dynamic.

First, for each of these modelling challenges, real world data sets are important for calibration. For example, studies of how much more adoption we can expect in locations where peers have already adopted can inform the role of information transmission in agent-based models (Appendix 1). These effects can mediate technology adoption as well as behavioral changes related to energy use (Wolske, Gillingham et al. 2020).

Second, 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 the full potential of HwL options.

Third, 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 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 (0-5% per doubling of cumulative experience) due to limited learning and experimentation effects (Sweerts, Detz et al. 2020, Wilson, Grubler et al. 2020).

Similarly, adoption rates for granular, distributed solutions under high peer effects 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 a 80% replacement in end-use technologies (e.g., fuel cell trucks) and slower still for lumpy capital-intensive upstream supply infrastructures such as hydrogen production and distribution (Grubler, Wilson et al. 2016).

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, Shehabi et al. 2016). Direct impacts associated with embodied

and operational energy used in ICT devices and infrastructures are non-trivial, around ~2-4% of global electricity use (Freitag, Berners-Lee et al. 2022). However they are likely small relative to the indirect impacts of digital services or applications that can either *reduce* energy use (e.g., efficiency, optimization, management, control) or *increase* energy use (e.g., direct or indirect rebound, intensification, novel applications) (Wilson, Kerr et al. 2020). 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, particularly at the intersection between DLS and innovation, while mitigating and minimizing risks of rebound.

For modelers implementing discrete digitally-enabled 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 digital innovations which include the risk of increased emissions due to inefficient substitutions, induced demand, and rebound effects (Creutzig, Roy et al. 2022). In implementing the High-with-Low scenario, modelers should use effect sizes towards the lower end of these ranges given scenario assumptions that rebound is carefully managed through purposive governance and coordination. In the Appendices, we provide similar data on the effects of digitally-enabled technologies and consumption practices in residential, mobility, and food sectors that are consistent with High-with-Low narrative and outcomes based on recent quantitative syntheses (Wilson, Kerr et al. 2020).

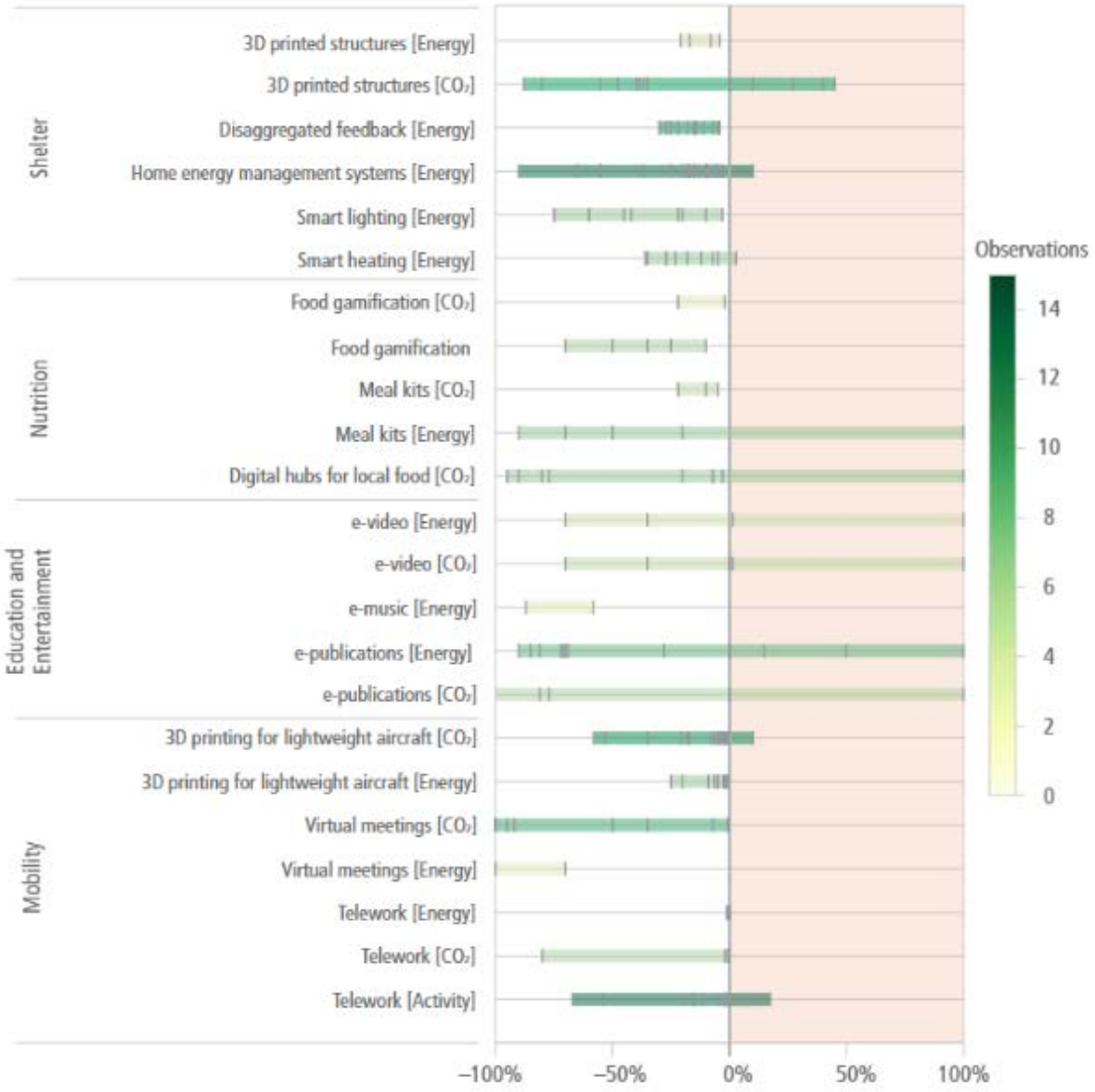

Figure 5. Synthesis of estimates of net changes in CO_2 emissions, energy use and activity levels as an indicator of mitigation potentials from end-user oriented digitalization. Source: Figure 5.12 in Chapter 5 of the Working Group III contribution to the IPCC's sixth assessment report (Creutzig, Roy et al. 2022).

Governance to achieve the High-with-Low scenario

Governance and institutions are integral for High-with-Low futures because each of HwL's central themes - decent living standards, innovation, and digitalization - depend on coordination functions. Based on the HwL dynamics discussed above, here we describe four aspects of HwL governance: shared expectations about direction of change; orienting incentives towards public purpose; infrastructure coordination; policy experimentation. In each case, governance plays an enabling function of corralling a highly distributed program of transformation towards HwL goals. Governance also serves a controlling function in each case to mitigate risks which are pervasive in this emerging area. Managing these risks is likely to be consequential to

achieving a transition to HwL. We thus address risks in this section as well as in the concluding discussion below.

Shared expectations about direction of change

At a macro level, governance can establish shared expectations about the direction of change. For the High-with-Low scenario overall, these coordination and regulation needs for each of the three central themes—decent living standards, digitalization, and innovation—need to be integrated into a coherent and synergistic approach to HwL governance. This involves creating expectations, widely shared within and across societies, of a High-with-Low future through a broad mix of policies to support HwL innovation that are comprehensive in scope, and ultimately need to be local in their implementation to reflect heterogeneous adoption contexts. This includes orienting innovation and digitalization 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.

Shared expectations can help diffuse successful HwL approaches by reducing risk-aversion in adoption and shifting the balance of considerations towards positively oriented peer-effects. With a supportive institutional environment in place, early adopting peers act as trusted information brokers to support positively self-reinforcing social network diffusion processes for HwL approaches. A real risk to a HwL future is aversion to change; that skepticism about the possibility of transformative change can be self-reinforcing. Governance can play a role in mitigating this risk through a process of developing a societal vision that a HwL future is realistic and probable.

Orienting incentives toward public purpose

On a micro level, governance provides rules and incentives to orient change toward public purpose. Innovative activity, especially via digitalization 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 behaviors. High-level reports, syntheses, and position papers have detailed the importance of governance for the entwined digitalization and sustainable development agenda (TWI2050 2019, Digitalization for Sustainability (D4S) 2022, Kaack, Donti et al. 2022, Pauliuk, Koslowski et al. 2022). Policies, rules, regulations, norms, and other governance institutions for digital applications can re-orient activity toward HwL outcomes. For example, they can tackle digital exclusion and facilitate universal access to digital skills and infrastructure, regardless of location, income, employment, or age. They can support democratization and participation in the workplace to help transform unsustainable industries and jobs (Pichler, Krenmayr et al. 2021). 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). A particular risk for digitalization in pursuit of HwL outcomes is the potential for substantial rebound effects, as new services become more intensively used. Regulators can moderate rebound to avoid HwL solutions enabling more excessive consumption. For example, they can collect and analyze data on usage patterns and provide incentives for lower usage, or they can encourage re-use of shorter-lived devices and support the development of recycling infrastructure to encourage circularity.

Coordination of infrastructure

Governance is also crucial for coordination of infrastructure, both physical and digital. For example, 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 will require a massive scale-up of public investment alongside spatial planning and design thinking to ensure efficient provisioning systems with low resource footprints (Fisch-Romito 2021). It also includes integrating new forms of private service provision with public infrastructures to ensure overall system performance in meeting human needs. Public authorities and institutions can thus play a role in ensuring interoperability among providers and provisioning systems, including through standard setting. Further, they can co-design the rollout and deployment strategies for products, infrastructure, markets, business models, and regulations.

A key risk to mitigate is industry concentration, which can easily accrue via network effects in both hard and soft infrastructures. In particular, digitalization's winner-takes-all networks and platforms lead to market dominance. However these monopolistic practices give 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, trialling, rolling out, and competing to provide digital services across the different dimensions of decent living. These activities extend to 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. This could, for example, include ensuring digital citizenship standards that empower users with data rights and avoid predatory data harvesting that undermines agency and social institutions.

In some cases, these infrastructures create natural monopolies in which end-user and consumer rights protection is paramount, not just for pricing but also for access and maintaining choice. In others, competition can be supported alongside accessibility of private individual and community service providers to the market. Allowing for a range of new entrants therefore becomes an important governance function. Well designed and implemented governance can enhance standardization and interoperability including through new business models that can make use of shared platforms, while remaining open themselves to complementary innovations.

Policy experimentation

A key risk with the strong governance institutions and approaches argued for to deliver HwL outcomes is that policies become too strong, and thus develop rigidity and self-reinforcing characteristics. This can be problematic in a transition environment characterized by change and uncertainty. An approach to policy design that embraces experimentation is crucial for accommodating the inherent uncertainty in how these systems evolve at scale. This involves 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 the idiosyncrasies of local context. This is not only necessary for a HwL transition, it is also highly feasible; policy experimentation would take full advantage of the flexibility that the typical granularity in HwL approaches provides and the natural experiments that heterogeneity in local context supports.

Concluding discussion: feasibility of the High-with-Low scenario

Feasibility, risk, and speed in High-with-Low

In this final discussion we zoom out from the central themes, cross-cutting linkages, governance challenges, and model implementation approaches of the High-with-Low scenario to consider its feasibility, risk, and speed in absolute terms and in relation to alternative visions of a sustainable future.

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-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. 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 or geoengineering-scale carbon capture and storage.

However, as noted above, successful roll-out of High-with-Low strategies depends on effective governance across technology development, business model, market design and regulatory dimensions, all of which are subject to uncertainties and political economic pushback from incumbent interests.

The ambition of the Paris Agreement and UN SDGs means any implementation pathway will be transformative and strongly discontinuous from historical trends. The 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, utilization, 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).

The High-with-Low development pathway sees a significant decoupling of energy 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. However, this will not emerge endogenously unless powerful lock-in constraints including vested interests are overcome (Schaffartzik, Pichler et al. 2021).

Our High-with-Low development pathway also 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).

Next steps for High-with-Low

The HwL narrative and its guiding decompositional quantification within the DETRAS framework aim to support quantitative scenario modelling activities within the EDITS[7] community and beyond. These modelling

[7] The Energy Demand changes Induced by Technological and Social innovations (EDITS) network is an initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA), and funded by the Ministry of Economy, Trade, and Industry (METI), Japan

efforts range in both scale (from national to global models) as well as in sectoral detail and scope (from sector-specific modelling such as in transport all the way to full coverage of all salient human activities). As such we intend this working paper on the HwL scenario narrative to serve as a "living document" that should be revisited again at a later stage once experience with HwL modelling accumulates and novel needs for deepening and/or widening the HwL narrative become clearer. Several potential areas for further work have also been identified in the iterative process that led to this current HwL scenario working paper. We list a few here to suggest possible areas of further research and conceptualization:

- More explicit consideration of food use and production and its associated environmental footprint (land use, water, biodiversity).
- More explicit consideration of distributional aspects including not only consideration of well-being "floors" but also starting to engage in a wider discussion on the non-linear relationships between levels of service provision and wellbeing under the sufficiency rubric, including possible wellbeing dis-benefits of overconsumption.
- Extending the HwL narrative and DETRAS quantification to differentiate between stock and flow variables, particularly important for materials and for the determinants of wellbeing (human, social, knowledge and manufactured capital and infrastructures).
- Developing richer narratives around governance and market organization forms and associated institutional settings that reflect both historical and social path dependency as well as invite thinking about possible innovations and their resulting impacts.

Appendices

Modelling approaches to capture peer effects, network effects, and standardisation

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 accelerate change (Edelenbosch, McCollum et al. 2018). However, these attempts to endogenize peer effects are the exception not the rule.

Second, 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). Network effects are included in modelling tools 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.

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 be 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.

Quantitative impact of digitalization on residential energy service provision

Figure 6 shows the effects on activity, energy or carbon outcome indicators from the adoption of digitally-enabled technologies and practices in the home. These are all examples consistent with the High-with-Low narrative and its emphasis on digitalization as a central theme. Similar quantitative syntheses are available for mobility and food-related innovations from the same source (Wilson, Kerr et al. 2020).

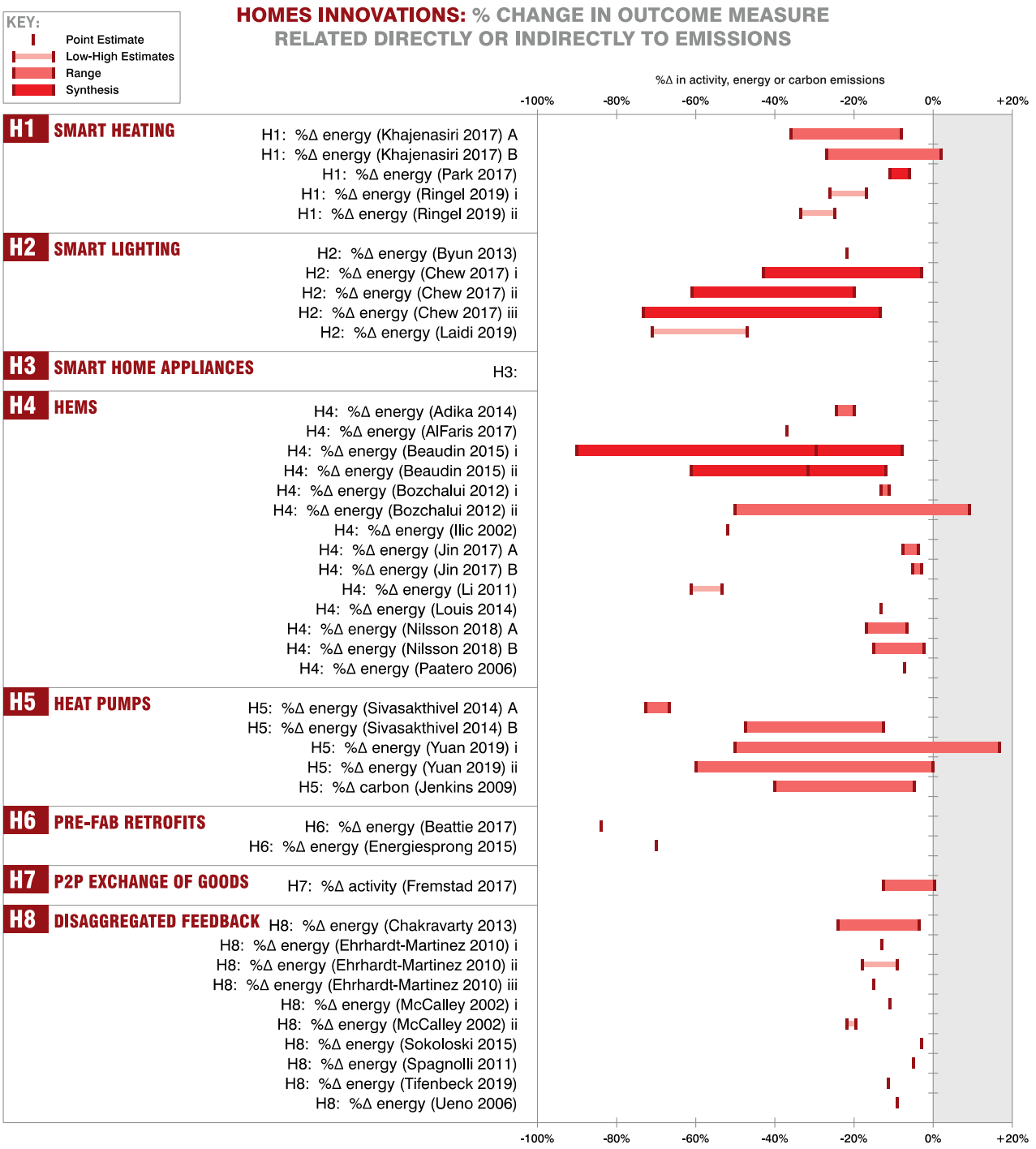

Figure 6. Synthesis of estimates of net changes in CO_2 emissions, energy use and activity levels as an indicator of mitigation potentials from digitally-enabled LED technologies in the home. Note: similar estimates are available for digital mobility and food innovations. Source: (Wilson, Kerr et al. 2020).

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Perspective

Technological innovation enables low cost climate change mitigation

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Scenarios

ABSTRACT

Scenarios from integrated assessment models play a central role in helping policymakers envisage pathways to limit global warming to well below 2 °C. We demonstrate that many models maintain a preference for inefficient combustion, in particular by relying on coal and bioenergy. In contrast to recent evidence from innovation studies, scenarios are optimistic on deployment of lumpy energy-systems technologies, such as carbon capture and storage, while insufficiently reflecting empirically observed innovation dynamics in more granular technologies such as solar photovoltaics. Our analysis shows that two key options for rapid decarbonization remain systematically undersampled in models that underpin IPCC scenarios: A) strong growth in intermittent renewables, in particular solar PV, together with electrification of sectors; and B) widespread adoption of efficient end use technologies enabling high service provision at low levels of energy demand. A combination of continued PV growth and sector coupling with low to medium energy demand (a corridor of 250 to 500 EJ of primary energy) would render carbon neutrality by 2050 feasible, thus enabling near-term cost-effective climate change mitigation and reducing the need for carbon dioxide removal in the 2nd half of the century. Models would benefit from updated cost assumptions, higher resolution on granular end-use technologies, higher resolution on sector coupling, and an overall consideration of demand-side solutions. Such updates – of which some are starting to be explored by modeling teams - are likely to demonstrate that some mitigation pathways are cost saving, rather than costly.

As societies work to limit global warming to well below 2 °C as enshrined in the Paris Agreement, they rely on insights from model-based scenarios to identify efficient pathways to decarbonization. However, comparing these pathways to empirical evidence on technology adoption raises concerns that these scenarios have a systematic bias both towards fossil fuels and towards large-scale lumpy technologies. For example, 3 out of the 4 illustrative pathways selected in the IPCC's recent special report (SR1.5), and 93 % within the full scenario ensemble, rely on high deployment of carbon capture and storage (>5GtCO_2 sequestered in 2050), a lumpy technology with large unit size and high investments costs that has not met the deployment targets set by the industry. These scenarios also do not feature levels and rates of technological learning and upscaling in renewables observed already over the past 10 years.

We systematically analyze the SR1.5 database of 416 mitigation and baseline scenarios and observe four sources of bias: a) baseline scenarios depend on fossil fuels – particularly coal – much more than historical trends indicate; b) bioenergy with carbon capture and storage (BECCS), as well as other carbon dioxide removal technologies, are upscaled quickly and draw high amounts of CO_2 out of the atmosphere; c) renewable upscaling and adoption rates are modest; and d) energy efficiency and demand reduction are only scarcely reflected. Climate protection scenarios like these provide valuable evidence for understanding net-zero transition dynamics. To remain policy-relevant in the future, a new generation of models needs to improve the representation of technology learning and diffusion (particularly regarding the granularity of technologies), more directly reflect real world dynamics, and draw on evidence from the economics of innovation literature.

1. Preference for coal

Coal features prominently in baseline scenarios. The shared socio-

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economic pathways (SSPs) indicate five distinct trajectories of demographic and socioeconomic changes through 2100, serving as a robust backdrop with which to evaluate climate policies [1]. While the baseline SSPs are designed to explore a wide range of global changes, ranging from "sustainability" to "inequality", they have one feature in common: they all rely heavily on coal [2]. Per capita coal consumption has stayed constant globally since 1950, with the exception of 2002–12, when it temporarily rose due to expanding Chinese coal use. Baseline SSPs are strongly skewed towards high coal trajectories, with per capita coal consumption increasing in all SSPs but SSP1. In SSP2 ("Middle of the Road"), coal grows 3 to 6 times faster than its historically observed average annual growth and in SSP5 coal grows 8–13 times faster [3]. Only the most optimistic scenario, SSP1 ("sustainability") keeps per capita coal consumption constant, thus roughly replicating historical experience. Overall, benchmarking scenarios for investigating climate stabilization are systematically biased towards higher coal dependence than what appears plausible from historical evidence (Fig. 1A). In 2050, only 2 % of SR1.5 baselines are more conservative than history (lower value than the minimum per-capital coal consumption over 1965–2019). In contrast, close to 25 % of baselines have twice as much coal than the mean historical values over 1965–2019. Despite the diversity of extant and emerging energy supply technologies, in these scenarios only natural gas and biomass contribute substantially to primary energy, aside from coal (Fig. 1A) [2].

By design SSP reference scenarios do not contain *additional policies* [4], but the models are calibrated on data that do include current and past policies, which are expected to continue into the future. Therefore, the *no additional policy* assumption does not explain the strong deviation from long-term historical patterns of coal use and the failure to phase-in renewables as empirically observed in recent years.

2. Coal as mitigation technology?

Coal remains a dominant energy source not only in baselines also in many mitigation scenarios (Fig. 2). For example, in the scenarios underlying the SR1.5, 34 % of all scenarios display rapid coal phase out, 3 % delayed phase out, 41 % coal persistence, and 22 % coal resurgence [3]. Coal intensive pathways in climate policy scenarios occur because coal is affordable, can be combined with CCS, and is assumed to not face substantial competition from alternative low carbon technologies. However, we can currently observe many markets where other technologies out-compete coal, even with only modest climate policy [7]. This is evidenced by the 653 GW of coal-fired power plant projects that have been abandoned in several countries, including China and India, since 2016 [8] (compare those cancellations to 64 GW/yr of new coal capacity coming online between 2016 and 2021 [8]). An additional motivation for regional and national administration is also clear: The health benefits of better air quality due to coal phase out are sufficient to motivate local action and negate global free-rider dynamics [9]. Further, hopes of rapid diffusion and adoption of CCS technology at the beginning of the century did not materialize [10]. Despite nearly two decades of effort, only two full scale CCS power plants exist, one of which recently shut down [11]. Modelled scale-up of CCS is in many scenarios much faster than for any other technology (Fig. 3). Averaging mitigation scenarios from SR1.5, CCS is applied to 28 EJ of the coal consumed in 2050 out of the total 40EJ of coal consumed. This implies hundreds of large coal facilities with CCS and dramatically contrasts the observed modest CCS deployment of mostly industrial facilities to date, casting doubt on whether such results are realistic. Low deployment and cancellations for CCS are the result of high capital costs, uncertain revenue streams, and low technological readiness [10].

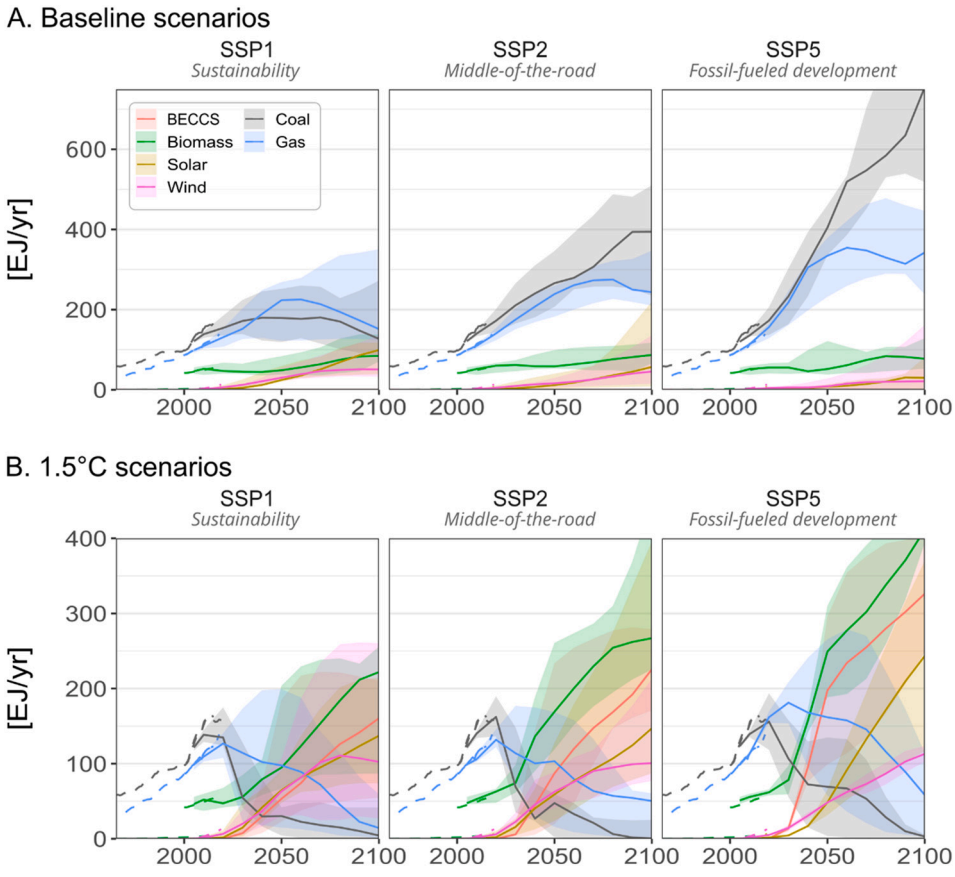

Fig. 1. Climate stabilization scenarios display high dependence on carbon-based energy carriers, coal in baseline, and coal and biomass combined with CCS in mitigation scenarios, insufficiently reflecting the high potential of solar PV. A) Shared socio-economic pathway (SSP) scenarios show high growth in coal consumption for primary energy. B) Mitigation scenarios building on SSPs show high deployment of bioenergy and BECCS. Nuclear is not shown here for clarity of presentation. Mitigation scenarios in integrated assessment models are constrained by the amount of carbon that can be emitted or a global maximal temperature, which cannot be exceeded at all or at the end of the century. In contrast, reference baseline scenarios do not have these kinds of constraints but either assume that carbon emissions are not constrained at all or that they are only limited by the currently implemented or announced policies (for details about the underlying data base see Supplementary Information). Overall, results display some but limited regional differences (see Supplementary Information).

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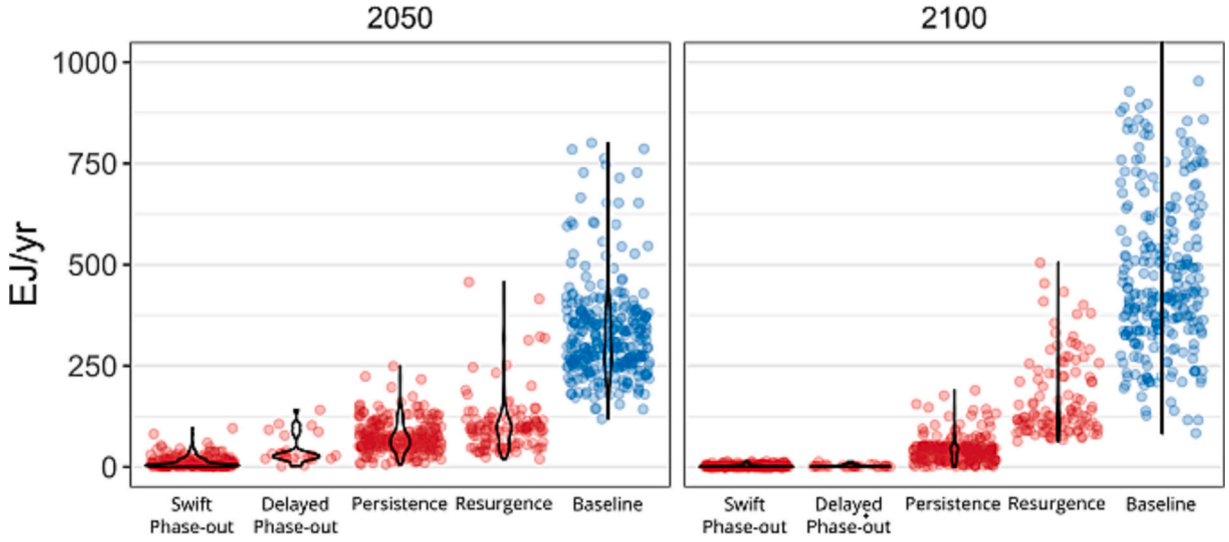

Fig. 2. Coal in mitigation scenarios. In mitigation scenarios, four different types of coal deployment occur, with coal persistence and coal resurgence scenarios showing continued dependence of coal, coupled with CCS. Scenarios here comprise those used for the IPCC AR5 and the IPCC SR1.5 [5,6].

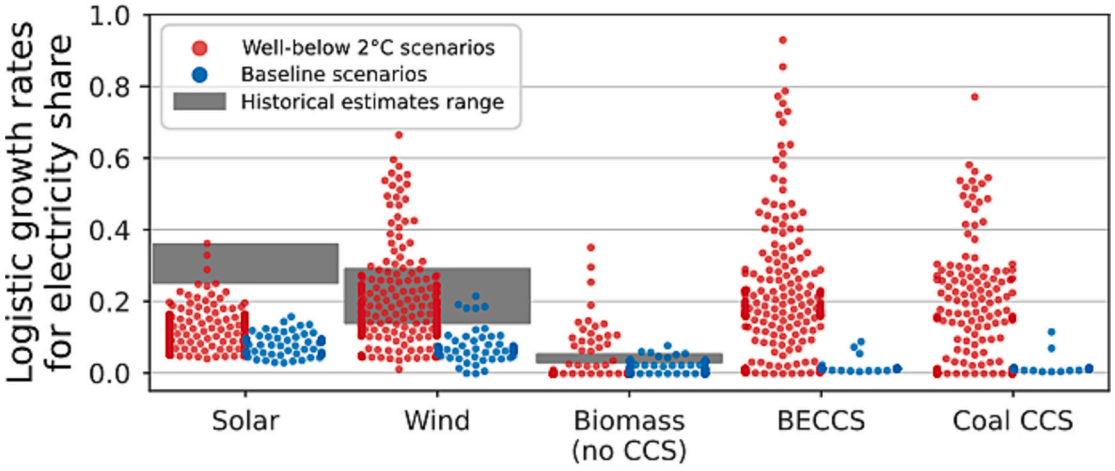

Fig. 3. Historical and modelled logistic growth rates of mitigation technologies. Models show bioenergy and CCS growth rates far above historical observations, and PV (and to lesser degree wind) growth below historical observations. Each point indicates the estimate of the growth rate parameter of a logistic fit to the share of a technology in the electricity mix for scenarios in the SR1.5 database.

3. Bioenergy replacing coal

In well-below 2 °C scenarios, models often replace baseline coal with bioenergy, while wind and solar provide low to intermediate levels of useful energy. Common types of bioenergy include wood pellets from fast growing forest plantations and biogas from the digestion of biogenic materials such as agricultural waste, maize or switchgrass. Bioenergy - with or without CCS - is in many cases the major source of energy providing 7–54 % of total primary energy in 2050 – tripling to quintupling from today's levels to 120–200 EJ. Mitigation scenarios model 100–400 EJ biomass in 2100 (Fig. 1B). In 2050, 65 % and 79 % of scenarios have >100 EJ of bioenergy with and without CCS, respectively. In contrast, solar and wind are modelled at about 50 EJ each in 2050 and 100 EJ for wind and 150 EJ for solar photovoltaic (PV) in 2100. Underlying reasons for models' preference for bioenergy include its versatile use and many different deployment pathways, while the negative environmental and social impacts of bioenergy, as well the challenges of polycentric governance of land use remain underrepresented [12,13]. This shows that carbon-based primary energy remains at the center stage of integrated assessment models, even in scenarios consistent with the goals of the Paris agreement.

Many scenarios – particularly those that limit global warming to 1.5 °C – heavily rely on BECCS. However, the models' preference for bioenergy is persistent and sometimes even larger when BECCS is not permitted, as options for decarbonizing the economy get more limited (in the models) – particularly in transportation (partially because of insufficiently reflecting the potential of electrification in passenger cars and heavy trucks) [14]. The growth rates of BECCS –a large-scale energy technology with huge investment requirements - are also much higher in models than what has been observed in recent decades (Fig. 3); realizing those rates would require a fundamental shift in CCS diffusion and adoption that is hardly perceived today. Globally at present, only one full-scale plant combines the two components and counts as BECCS (producing ethanol) [18].

The high demand for bioenergy and BECCS has implications for land-use and thus non-climate planetary stability [15–17]. Most scenarios are inconsistent with a precautionary threshold of 0.5 Mkm^2 land for bioenergy, corresponding to today's usage, and aiming to protect half earth for biodiversity [19]. Of the scenarios in the SR1.5 database that present land use, 97 % (126 out of 132) are above this precautionary threshold

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[20]. The sustainability threshold for BECCS specifically has been estimated at between 0.5 and 5 Gt CO_2/yr in a systematic review [21]. Across all scenarios, 91 % are above the lower threshold in 2050, and 33 % are above the higher threshold [20]. Out of the 4 illustrative pathways in the IPCC Special Report "Global Warming of 1.5°C" (SR1.5), 3 rely on BECCS; their cumulative carbon dioxide removal (CDR), corresponds to average sequestration of 3 Gt CO_2/yr, 8 Gt CO_2/yr, and 20 Gt CO_2/yr between 2050 and 2100 [5]. This huge demand for bioenergy makes these scenarios incompatible with other sustainable development goals, such as "zero hunger" (SDG 2) and protecting "life on land" (SDG 15).

The high demand for BECCS in models strongly depends on demand for CDR (Fig. S1), which in turn is an artifact of a particular modeling assumption [22]. We suggest an updated scenario design logic that explicitly considers peak warming [23]; this would highlight the importance of emissions reductions between now and 2050 to avoid the dependence on risky mitigation strategies. Out of 53 'as likely as not' 1.5 °C scenarios, the majority (34 scenarios) model a low overshoot to 1.6 °C and end-of-century stabilization at about 1.3 °C. This high reduction below 1.5 °C in 2100 is intended to increase the likelihood that 1.5 °C is not crossed to >66 %. A reduction by 0.3 °C roughly requires additional CDR of about 700 Gt CO_2. However, in 2050 we are much more likely to understand the transient climate response to emissions, and would only need to apply that high amount of CDR if the transient climate response to emissions is higher than expected [24]. This case would require high amounts of CDR just to maintain temperatures at 1.5 °C or 1.6 °C, if possible at all. If transient climate response to emissions is below or at current estimated values, the demand for CDR will be much lower, with cumulative negative emissions below 200 Gt CO_2 until 2100. Together, this reveals that high CDR and BECCS deployment in models depend on very specific assumptions at the end of the century.

4. Underestimated solar PV

Energy models lag real-word developments for renewables [26]. Climate stabilization scenarios assume that PV will grow, but much slower than it has over the past two decades, such that it contributes only modestly to meeting global electricity demand, reaching levels of 20–50 EJ in 2050 [27]. The same models also project PV levels of 30 EJ (POLES) to 100EJ (REMIND) in 2050 if CCS technologies and nuclear are banned [27]. Other model runs provide 100–150 EJ from PV in 2050 (Fig. 4). Eighty percent of well-below 2 °C scenarios have <50 EJ of solar PV in 2050. Meanwhile, new scenarios, published after the IPCC 5th Assessment Report, many of which originate from outside the integrated assessment community, find much higher shares of intermittent wind and solar in decarbonization and energy system pathways (Fig. S2, [28]). A statistical analysis demonstrates that models used scenarios from integrated assessment models systematically project lower PV adoption pathways compared to more granular energy systems models, in part because many IAM scenarios assume higher capital costs [29]

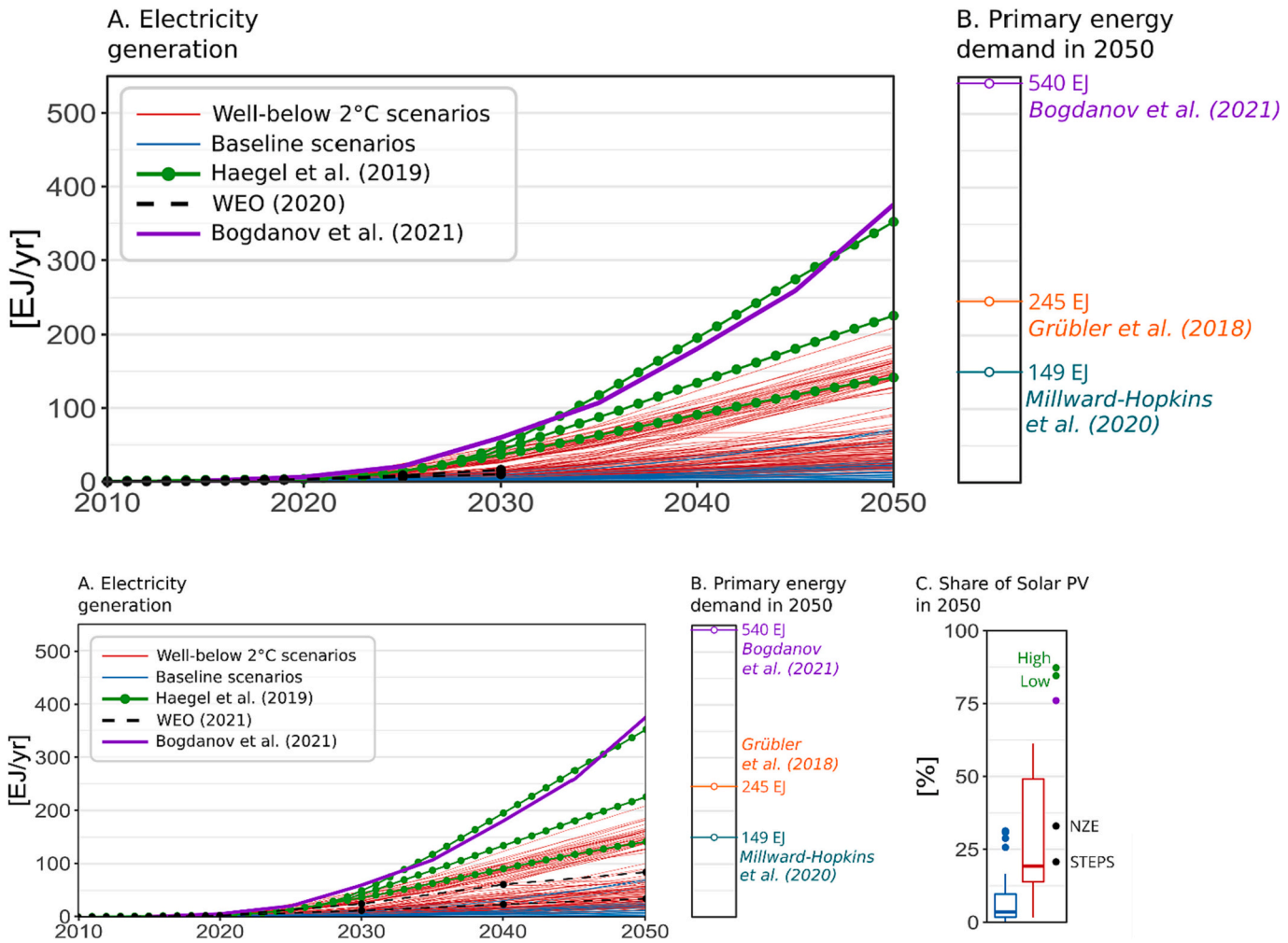

Fig. 4. Electricity from solar PV in mitigation scenarios (A) and primary energy demand (B). Projections from solar experts [25] show double or triple rates of electricity from PV compared to integrated assessment models. Electricity generation by solar and wind, coupled with wide-ranging electrification of transport, heating, and industry can satisfy total primary energy demand in low to medium energy demand scenarios in 2050.

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(Fig. S2). In contrast, energy modeling demonstrates that the steep cost decline of solar PV not only enables rapid decarbonization of the power sector but also catalyzes the integration of other energy technologies required for a highly sustainable energy system, in particular, battery storage and electrolyzers [30]. PV technology experts expect that PV could deliver 125–350 [central estimate: 225] EJ/yr by 2050, which is twice as much as coal provides in 2020 [25] (Fig. 4) (Similar magnitudes were also modelled in [31–33]). For comparison, a low energy demand scenario projects 245 EJ of total primary energy in 2050 [34]. The historical experience of solar PV—growing at 30 % annually over the past twenty years and continuing to fall in costs—suggests that PV modelers' scenarios are more consistent with historically observed trends than are the climate stabilization scenarios of IAMs (Fig. 3). Modelled growth rates in wind are more in line with historical observations. While most scenarios envisage growth rates below historically observed data for wind, other scenarios project growth rates more than double what has been observed (Fig. 3).

Possible reasons for this bias against renewables include reliance on theoretical assumptions (theory of learning by extraction) [2], insufficient gauging of growth rates of renewables [35], and limitations of intermittent renewables by mandating baseload supply. Related explanations identified in meta-studies of PV in scenarios assessed by the IPCC include lack of electrification beyond the power sector and high PV capital costs, including many scenarios in which 2050 costs are above current costs [28] (but see [36]). A notable finding is that future PV growth rates in scenarios from granular energy system models are not only higher than those in IAM scenarios but have been increasing over time [29], which is what would be expected as their falling costs lead them to beat fossil fuels on cost in more and more situations [37]. IAMs also include technical constraints that may slow variable renewables' growth, such as higher integration costs at high shares of variable renewables and additional costs due to electrification of sectors that depend heavily on solid, gasified or liquid fuels. A specific concern is that IAMs lack hourly resolution of electricity supply and demand, rendering modeling of the integration of intermittent renewables difficult – even though first teams have started to address this. In turn, models assume integration costs of 23 $/MWh for solar and 37$/MWh for wind in low-penetration scenarios (<20 % of demand) [38], costs that increase to above 100$/MWh for higher penetration [39]. The higher costs reflect assumptions of grid integration of intermittent renewables. However, detailed energy system models project levelized costs of electricity (LCOE) considerably below 100$/MWh for 80–100 % intermittent renewable energy systems [40,41].

At high levels of intermittent renewables, the LCOE of electricity generation plus storage or demand-side management must be considered. Modeling studies suggest that between 15 % and 24 % of electricity demand will be covered by storage in 2050 high renewable energy scenarios [42]. Affordable storage will rely mostly on utility scale and prosumer batteries and, to smaller degree, and pumped hydro energy storage.

Evaluation of optimal PV plus battery storage (capacity of 4 kWh/kW_P) at recent battery costs ($350/kWh, 15 years lifetime) suggest that adding storage doubles LCOE compared to PV only, while remaining below the household costs of electricity in different locations worldwide; assuming continued battery innovation through 2030 ($200/kWh, 30 years lifetime) results in a system cost 28 % above a PV-only system [43]. Even that estimate might already be outdated, as global weighted average lithium ion battery prices were already below $100/kWh in September 2023 [44]. Even today, PV plus battery systems allow a rates of return of 9 % in Hawaii and 4 % in Germany [45]. These values demonstrate that the demand for storage is a highly relevant cost factor but consistent with competitive renewable energy systems [46,47].

At least one integrated assessment model, REMIND, has been updating its assumptions on integration costs, leading to a substantial increase in intermittent renewable shares of electricity supply [36,48]. Several models have also included hourly resolution [49,50], but results have not yet made it into the canon of integrated assessment modeling. As a result of these assumptions on PV and the broader energy system, biomass remains a preferred option in IAMs. It is valued for its flexibility as energy carrier in different sectors, for example in transport, and in some models for its contribution in providing baseload electricity. In turn, intermittent renewables are limited, because demand flexibility and storage technologies are assumed to be costly or not represented in models. Demand-side solutions, e.g., load smoothing via price signals, are only beginning to be considered in a portion of new scenario runs.

5. Granular end use technologies

The dynamics in solar discussed above represent a broader phenomenon increasingly observed: granular technologies—those with small unit size that are amenable to scale through modular aggregation—show much faster innovation dynamics than large scale technologies (Fig. 5) [51]. Granular technologies learn faster and become adopted faster, because they involve lower risk, involve many more iterations and thus opportunities for improvement, and are suitable in a much broader variety of adoption contexts. Most demand-side technologies are granular [51,52] since they are almost always small scale. Examples include heat pumps, lighting, appliances, windows, and batteries (Fig. 5). The enhanced dynamics observed in granular technologies point to a much larger potential for reducing energy demand as those technologies also improve and become adopted more quickly. In addition, novel service provisioning systems enable the satisfaction of needs and wants while reducing associated primary energy demand and GHG emissions [53,54]. Examples include compact cities that increase accessibility while reducing travel distance demand [55], flexitarian or vegan diets that are healthy and tasty while reducing meat production [56], and the integration of electronics into a single device [34]. More efficient end-use increases services consumption (rebound), but that increase is typically about a third, which does not affect our conclusions and can be mediated by policy design, such as pricing carbon.

Energy demand scenarios based on granular end-use contrast with high energy demand in many IAMs. In all SSPs, energy demand rises from 580 EJ primary energy in 2019 to above 700 EJ in 2050 and in SSP5 to >1200 EJ in 2100. This is more than twice the current level (in non-mitigation scenario this demand is mostly satisfied with coal, Fig. 1A). In contrast, recent models that take a service provisioning perspective, driven by granular demand-side technologies and service system configurations, show that a global reduction of >40 % in primary energy use between 2020 and 2050 is possible and consistent with conditions required for high quality of life [34,57]. Importantly, the 245 EJ modelled in a low energy demand scenario for 2050 [34], and the 149 EJ minimal energy required for a decent living for all in 2050 [57], are within the potential for what PV can provide, even in some integrated assessment scenarios (Fig. 4).

Rapid innovation extends beyond solar (Fig. 5). Onshore wind, offshore wind, as well as mobile and stationary batteries have shown similar learning for many of the same reasons: modularity, massively iterative manufacturing, and simplification that comes from shifting much of the most cutting edge technology to production rather than in devices themselves [58,59]. As a result, in just the past 10 years, the cost of electricity from solar has fallen by 87 %, wind by 38 %, and battery storage by 85 %. Wind and solar have grown from 1.4 % of global electricity supply in 2009 to 10.2 % in 2021 [60], and they continue to grow, as a variety of new countries adopt them. While not pervasive yet, one can observe profit maximizing firms shutting down existing coal plants and replacing them with new hybrid solar-battery systems, even in markets with no carbon price or other climate policy; in an increasing number of places building new solar is cheaper than just the operating costs of coal plants.

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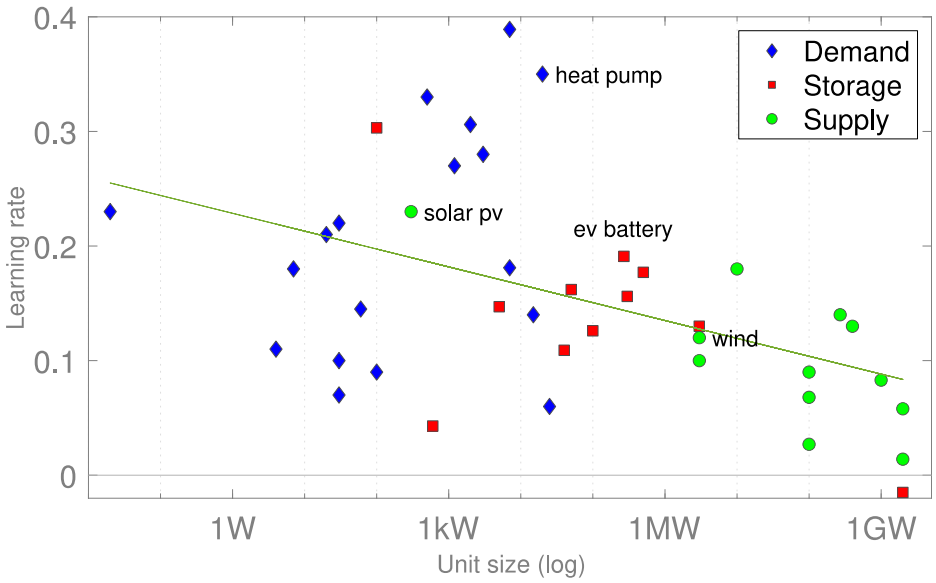

Fig. 5. Demand technologies show high learning rates. Learning from small-scale granular technologies outperforms learning in larger supply side technologies. Line is linear fit of log unit size to learning rate for all 41 technologies plotted.
Source: [52]

6. Low cost climate change stabilization feasible

Technological learning and the observed bias in climate stabilization models have major implications for climate change mitigation and associated policies. Solar and wind are now cost competitive with fossil fuels in most world regions [37], resulting in constantly reduced cost estimates of investments required to curb global warming [61]. The reductions in costs described above have led to levelized cost of energy (LCOE) for unsubsidized solar PV and wind of 30–41 $/MWh and thus outcompeting the marginal cost of electricity from coal [62]. In the first half of 2020, 80 % of private investment in new energy capacity was in renewables [63]. The falling cost of storage is leading to widespread adoption of battery storage (10s of GWs), extending the availability of variable renewables for several hours and further enabling their adoption. As renewables obtain higher market shares, the capacity factor of fossil-fuel based coal and gas plants declines rapidly, which in turn increases their LCOE. This reduces construction of new plants, and to the extent that some operational costs are fixed, hastens the retirement of existing plants [64]. Air pollution is also a major reason for coal power plant retirement, while maintaining jobs in coal mining is a reason to keep even economically unattractive coal infrastructure running. In fact, low-cost renewables foster mitigation even when only weak climate policies are present, while alone falling short of ambitious climate mitigation goals [65].

A key mechanism for rapid decarbonization with intermittent renewables is sector coupling, i.e. direct and indirect electrification of transport, heating, and industry via power-to-X processes [30] (Power-to-X processes encompass processes to store electric energy in chemical energy carriers such as synthetic gas and liquid fuels; resulting products offer carbon-neutral products and fuels for the chemical sector, and for aviation and ships). While there is no consensus on the economic viability of 100 % renewable energy systems, a multi-sectoral, multi-regional cost optimal pathway for 145 regional energy systems indicates that stabilization at 1.5 °C can be achieved by 100 % renewable energy and sector coupling, while realizing substantial energy savings and providing lower cost energy compared with today [33]. Crucially, rapid electrification increases overall energy efficiency, thus enabling a decline of total primary energy demand from 450 EJ in 2015 to 280 EJ in 2035, while simultaneously increasing energy services provided; totally primary energy demand increases again to 540 EJ in 2050, roughly consistent with SSP1 specifications [33]. This variable renewable-based 1.5 °C pathway requires a >5-fold increase in electricity supply from 2015 to 2050, dominated by wind energy until 2030, and thereafter by solar PV. Heat pumps and electric heating will provide a share of >40 % of all heating by 2050. The associated capacity growth, especially in solar PV, is not constrained by materials, and could be ramped up to capacity levels beyond what is needed in 2050 [66]. This renewable focused energy transition would keep LCOE stable. Another energy system model finds that European levelized costs of electricity will fall from the current 69 €/MWh to 51 €/MWh, if 100 % of electricity is provided by renewables, mostly solar, and if grid interconnections are expanded [67]. Globally, higher capital costs of renewables are estimated to be overcompensated by lower cost energy sourcing, saving economies $400 billion over time [68]. These scenarios demonstrate that high renewable pathways are cost efficient. If matching a low to medium energy demand corridor of 250 to 500 EJ, high renewable deployment supports net-zero carbon until 2050.

While investment needs remain substantial, and access to finance in low and middle income countries is crucial, these results demonstrate that high PV scenarios are cost competitive in comparison to other future technology mixes and will even save financial resources in the medium term. Not only is a different set of technologies expected to deliver rapid climate change mitigation – intermittent renewables instead of biomass with CCS – but also the costs of climate change mitigation appear lower than previously expected and lower than those portrayed in IAM scenarios. Further, the history of innovation suggests that public support for innovation dynamics can generate booms for economies, rather than burdens [69].

7. Biases in models: considerations for modeling and policy interpretation

Although the IAM community is actively cooperating internally and with other scientific communities to expand the capabilities of their modeling frameworks [70–73], model improvements are not always widely implemented across IAMs leaving important biases in scenario ensembles (Table 1). Some biases are due to assumptions and others due to model structure; but all have implications for the use of scenarios within the IPCC and their interpretation by policy makers. As discussed above, a key bias is that IAMs are missing much of the innovation

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Table 1
Bias in integrated assessment models and consequences. Some biases are addressed by modeling teams and considerations are reflected in a few new scenarios. However, the majority of scenarios in ensembles, as represented in the IPCC, still fails to reflect these developments.

Bias in current modeling	Reason	Consequence of bias	Example of recent IAM innovation or relevant other models
Innovation dynamics	Insufficient modeling (exogenous or endogenous) of technology specific learning curves; insufficient focus on sector coupling	Technologies with high technological learning are systematically underestimated, those with stable cost profile overestimated	REMIND models endogenous learning for key technologies [77]; sector coupling and electrification gets attention in some scenarios [36]
Human behavior	No representation of green preferences in households or investors	Presents part of endogenous technological learning of green technologies (see above)	The agent-based model BENCH represent household decision and links to macro-models [78]
Other environmental issues	Air pollution major reason for phase out of coal	Phase out presented as sunk costs, insufficiently reflecting environmental (monetary) gains	Explicit representation of coal power plants stock, partially existing in IAMs [79], helps to identify co-aligning air quality control [80]; IAMs identify a renewable based strategy as co-benefit maximizing [27]
Social concerns	Coal miners main reason to keep inefficient coal infrastructure running; difficult to model endogenously	Stickiness of coal only represented in (outdated) monetary terms, not in real social concerns	Non-IAM: an alternative approach for modeling that includes distributional impact and market failures suggested [81]; job creation in power sector modelled [82]
Path dependence in modeling	Assumptions and dynamics remain legacy from older model versions, due to high labor costs of updating models and lack of intrinsic motivation, as the academic systems favors 'novel' insights over maintenance work	New dynamics (such as the reduced costs of PV) enter the mainstream of scenarios only after several years	Some scenarios investigate the role of declining renewable costs [36]
Cost assessments	Lack of updated costs of key technologies, such as PV, wind, and batteries, and only partial coverage of temporal resolution and flexibility management solutions	Climate mitigation framed as costs on GDP on economic terms	Non-IAMs point to cost savings in faster transitions to renewables due to lower cost energy sourcing [68]

dynamics that are rapidly changing energy systems across the world. We suggest that scenario models may need to refocus on using up-to-date data on adoption, costs, and learning to ensure that models remain useful for policy decisions [74]. From our perspective, we see three modeling innovations that deserve immediate attention: 1) updating of renewable energy cost assumptions and fuller representation of technological learning curves – particularly how granularity of technologies affects learning and upscaling; 2) more explicit modeling of sector coupling and specifically power-to-X technologies; and 3) including insights from hourly resolution modeling of energy systems [28,35,75]. Meanwhile, a consideration of energy system models that lack integrating climate considerations but maintain high spatial and temporal resolution in energy systems and up-to-date technology representation at decade long time scales, such as the LUT Energy System Transition model [33,76], would complement the century long modeling of IAMs in IPCC reports.

Other biases relate to behavioral dynamics, other environmental concerns and social dynamics. For example, green preferences lead to early adoption of granular low-carbon technologies [83], an effect that drives technological learning (see above). The costs of coal are also visible in high mortality associated with air pollution, and counterfactual benefits of cancelling coal power plant construction [84]. However, social dynamics, labor involving in coal mining and established power structures can obstruct the phasing out of coal [85,86].

Another key concern is the time lag and presentation of model results. It can take ten years or more to proceed from model update to publication, to reflection in assessment reports like the IPCC, to publication of IPCC reports, to mainstreaming of messages in the public. The length of these timelines in a context of rapidly developing technology can make policy messages outdated. With dynamic technologies like solar, wind, and lithium ion batteries, even using data 5 years old can mislead decision makers. To improve this situation, all steps of climate stabilization scenario generation and publication should be accelerated. Specifically, this likely will need to include: modular and more agile model structures, annually updated scenario databases and associated publications, and an emphasis on models gauged with most recent empirical data in assessment reports [74]. A higher diversity of models and scenario methods included in IPCC assessments would better represent multiple perspectives on intermittent renewables, sector coupling and energy end use [29,87]. At the same time, the desirability of full integration of all relevant dimensions should not sideline up-to-date consideration of technological learning and adoption. Hence, for presentation of scenario ensembles, the robustness of policy insights would improve if only the most recent scenarios were presented, even if overall number of scenarios would decrease substantially. Policymakers should interpret outcomes from scenario modeling as one set of possible futures while drawing insight from other sources of information as well, such as those described above including more temporally and geographically resolved modeling, as well as narratives describing possible futures.

Solution pathways based on systems consisting of renewable supply, energy storage, sector coupling, and granular end use are among the most cost effective. They are also the technologies that have dominated recent real world energy system dynamics. While fast transitions to renewables involve high capital costs, they are expected to save $400 billion over time due to lower cost energy sourcing [68]. Hence, there are good reasons to expect that global efforts to reduce GHG emissions can be done more cost effectively than widely assumed, which makes reaching the goals of the Paris agreement more feasible and thus more likely. Modelers should take this possibility seriously.

Data and materials availability

See Materials and Methods for references to the databases accessed.

Declaration of competing interest

Authors declare no competing interests.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2023.103276.

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EDITS
Energy Demand changes Induced by Technological and Social innovations

IIASA

RITE
Research Institute of Innovative Technology for the Earth

Annual Report

Energy Demand changes Induced by Technological and Social innovations (EDITS)

February 2024

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This document reports the research and coordination activities in the scope of the 'Energy Demand changes Induced by Technological and Social innovations (EDITS) project. The report includes an overview of the state of the EDITS project, an Annual Meeting summary, a commentary on the current state of LED representation in building sector modeling tools.

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PART 1. EXECUTIVE SUMMARY

This report provides an overview of the **fourth year of the "Energy Demand changes Induced by Technological and Social innovations (EDITS)" initiative.**

The report starts with an executive summary, highlighting the most important activities, achievements and scientific results (Part 1.). It continues with a description of EDITS set-up, working methods and research community building, reflecting on the changes that were implemented this year (Part 2). It is followed by reporting on the research and modeling activity of the EDITS network between March 2023 to February 2024, specifically providing a commentary on the current state of LED representation in building sector modeling tools (Part 3 and Part 4 respectively). Then we explain the efforts on engagement and outreach during the period (Part 5), and finish with an outlook to future directions (Part 6).

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.

The aim of the EDITS network is to identify and fill in gaps to enhance modeling, analyzing, and communicating the demand-side solutions for climate mitigation and its nexus in the global environmental and social systems, as summed up in Figure 1.

Figure 1. Aims of EDITS

GOALS AND ACHIEVEMENTS

EDITS has been moving from stocktaking and describing the challenges towards innovation and filling in the identified gaps in the running year 2023-24. This transition will be continued in the next and coming years, leading to conceptual strengthening, scenario development and modeling, as well as broader-scale data collection.

In February 2023 the EDITS community collectively identified goals to be achieved by February 2024. Table 1 summarizes the progress towards them and plans to progress further.

Table 1. EDITS specific goals and their achievements in the fiscal year 2023-24.

Overview of EDITS organization:	**Achieved in 2023-24**	**To be continued in 2024-25**
EDITS should continue with the existing WGs + Establish a new WG on Wellbeing	The basic structure of EDITS was kept with the Working Groups being the spine of the operational set-up. A new WG was established that aims at conceptualizing and quantifying wellbeing as an input or driver of the energy transition.	The eight WGs continue to form the basis of EDITS. Their working methods and content are under revision for the next year to ensure balanced capacity use as well as complementarity across and beyond the WGs.
Include extra streams, exemplified by the fast-tracks.	Six fast-track research activities were funded and two unfunded FT activities were carried out.	Five new fast-tracks are identified for funding.
Community plans to find ways to include members that are not well integrated in the current structure.	Research in fast-tracks and the new wellbeing WG allowed for members of very diverging disciplines to contribute and become more active.	Contribution to specific themes (fast-tracks) and WG work is encouraged by all disciplines. Fast-tracks represent cross-cutting issues.
Quarterlies are planned 3 times a year and the next Annual in 2023 is foreseen in Autumn 2023 in Lisbon, Portugal.	The planned Community meetings were held: 3 Quarterlies and an Annual Conference in Lisbon, Portugal. Besides, 60+ team meetings were also held.	Meetings are planned similarly as last year.
Working Groups shall meet on-demand to ensure progress.	While meetings were centered around WGs previously, these were refocused into fast-track meetings, specific WGs (mostly Protocol and Wellbeing), while other WGs targeted finishing research papers.	WG meetings are planned to be refocused in the coming year to become hubs for (a) discussions, (b) hosting fast-tracks, (c) cross-WG collaborations.
Outputs:		
Target number of paper is 15 between March 2023 and March 2024, and to achieve this:	The total number of papers by the Community with EDITS acknowledgement is 24.	It is planned to produce 15 papers in 2024-25.
1. Follow-up on special topics after the sectoral review papers;	Identified topics were partially followed up, and mostly channeled into fast work streams, some of which were funded via fast-tracks.	The plan is similar to 2023-24.
2. Sectors and data gaps;	The large model review papers are finished. Buildings review paper is published, while Industry and Transport are in the pipeline.	Instead of sectoral papers, it is expected that more work will be done in cross-sectoral and multidisciplinary levels.
3. Progress on low energy means scenarios;	The model complementarity exercise collected models, tested the indicators and compared Tier 1 variables.	A paper on HwL scenarios is planned to be written this year. Tier 2 variables shall be tried.
4. Fast-track papers.	The fast-tracks have already led to two specific papers, 5 are prepared to be submitted in a few weeks, and one more is in early draft.	At least five new papers are expected from the fast-tracks.
Outreach:		
Webinars: continue and organize about 2-4 webinars per year	3 webinars were organized.	At least 3 webinars are planned for the coming year.
Outreach events, policy events: COP, G7 and local events	EDITS participated at the COP28, International Vienna Energy and Climate Forum (IVECF) and other events. A policy meeting in India was organized.	The plans are the same for next year.
Research events: encourage presentation of results at scientific conferences	A Symposium was organized in Oxford on Technology and Global Change. EDITS attended scientific conferences, e.g. Industrial Ecology Conference.	The same aspirations are set-out for the next year.
Social media set-up and population	An X-account, a Linkedin group and a Facebook page were set up with regular posts on events and outputs.	The social media accounts will be continued. A public brochure will be created and the webpage will be developed.

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 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**. 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 2023-24, the key scientific progress[3] made by the EDITS community was:

- The new High with Low scenario narrative has been published (link here).
- The EDITS Community summarized the key missing elements of harnessing the benefits of low energy demand in a commentary paper in Joule, calling for (1) more diverse models and scenarios; (2) better data; (3) evidence on policies, societal actions, and business-models.
- Studies that looked at certain aspects of demand-side were carried out, for example on energy security (link)
- Reviews of low energy demand modeling in the demand sectors (buildings, industry and transport) have been finalized. Relatedly, the paper on buildings models is published in ARER, the paper on industry models is under review, and the transport model review paper will be soon submitted.
- Several studies specific to sub-sectors or sectors have been carried out by smaller teams. (1) Paper on digital convergence (link), (2) Buildings models (link and link), (3) Transport sector assessments and modeling (link, link, link, with four more papers drafted/submitted), and (4) industry sector assessment and modeling (link, link), and even looking at cross sectoral descriptions, such as mobility infrastructures (link) and cities (link).
- The metadata platform (started in 2022) was tested and launched: https://edits-project.sites.uu.nl.
- Studies related to specific demand-side data are under way: (1) identifying data gaps, (2) costs and potentials of demand-side solutions.
- Conceptual or wellbeing related papers focused on social innovations (link), technological innovations (link) or both (link), and characteristics (link), and policy (link)

In 2023-24, the number of publications, presentations and public outreach programs has further increased[4] reaching a total of 24 papers or book chapters with direct acknowledgement of EDITS. A further three papers have been submitted to journals and are under review, and nine more are in draft status and will be soon submitted for publication.

RESEARCH NETWORK COORDINATION

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.

[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/
[3] The full list of publications, reports, outputs are included in Part 3 (Publications) of this report.
[4] The full list of publications, reports, outputs are included in Part 3 (Publications) of this report.

The organization of the network has a flexible structure (see Figure 2). All EDITS members are part of the **EDITS Plenary**. The Plenary can view and comment on research, modeling, and other activities. The Plenary are invited to regular meetings, as well as webinars. The plenary have access to working materials on the shared working space. IIASA and RITE keeps regular contact with the whole community.

EDITS is organized into **eight working groups (WGs)**. 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 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, WG 3-Synthesis, and WG 3-Wellbeing.

Dedicated research is carried out within smaller teams. These can operate within the WGs, or as **fast-track streams** (FT). The fast-track scheme was launched early 2023 to facilitate fast paced, high quality, paper-oriented demand-side research. Fast-tracks are paid or non-paid activities, and may function as part of a WG or independently.

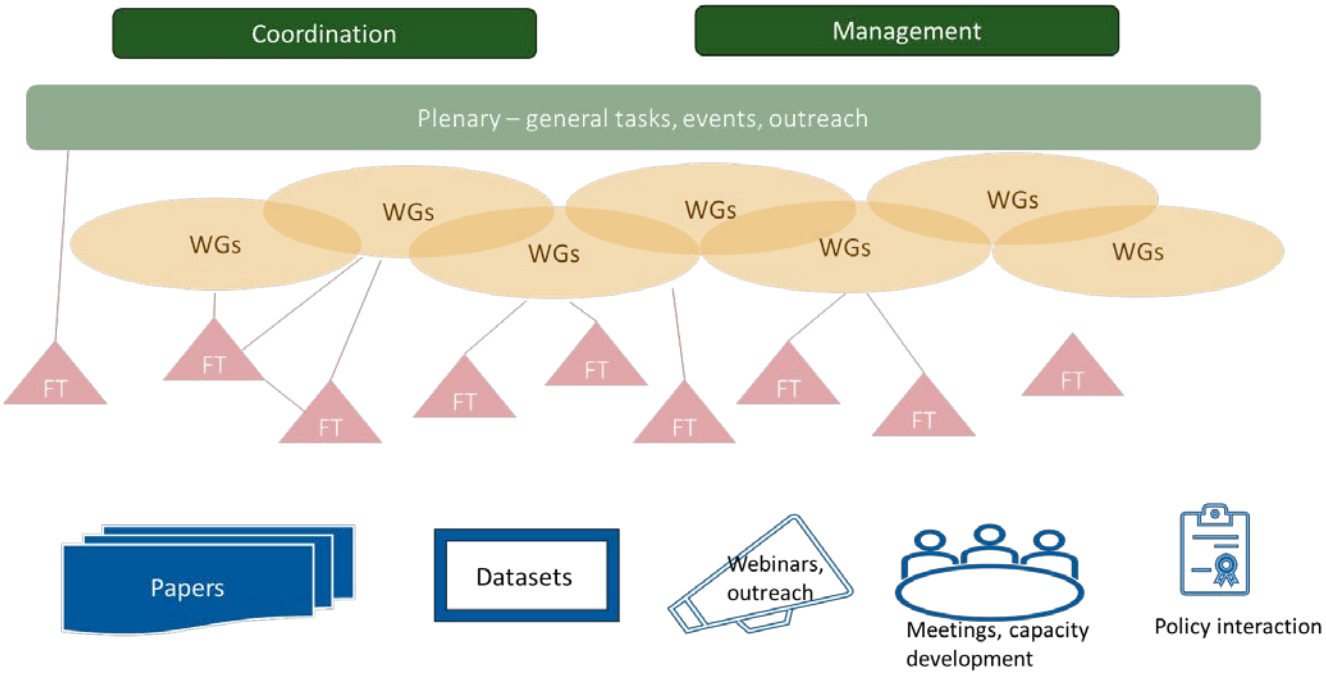

Figure 2. EDITS Network set-up and products. WG = working group, FT = fast-track stream

EDITS MEMBERS

As of February 2024, the EDITS network has **182 individual members** from **24 countries** (Figure 5 in Part 2.) representing **102 Research Teams**. This is almost 20% growth from 154 members in 2023 and 149 in 2022, including a few earlier members leaving EDITS due to e.g. change of workplace.

EDITS membership is by invitation only.

Members are free to choose their participation in the eight working groups (Figure 3) and other activities such as fast-tracks.

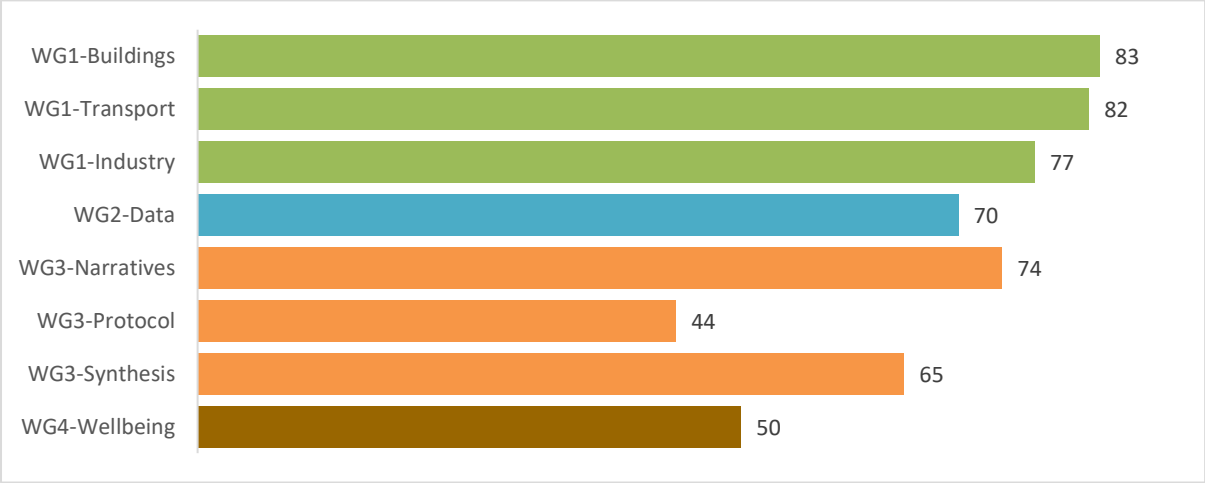

Figure 3. Working group membership as of February 2024

EDITS has been working with **31 demand models around the world** (Table 3) and was in contact with further 11 models (Table 4). 18 models of the identified 42, have a global coverage or focus, 21 of them are national and 4 multinational and one is at city level. This diversity makes it possible to develop a complementary modelling of different geographical levels and across sectors (Figure 5).

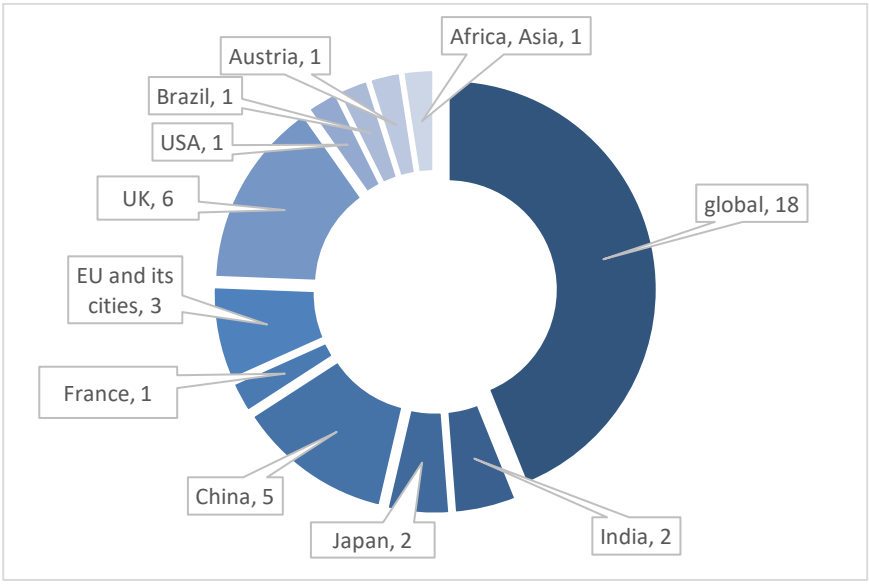

Figure 4. Coverage of the identified models within EDITS in 2023-24.

COMMUNITY MEETINGS

Intellectual and inspirational exchanges are organized in **Quarterly Meetings and an Annual Workshop**[5]. In 2023-24, three Quarterly meetings were organized online and one Annual Conference in person.
The Quarterlies are working meetings, focused on reporting and common discussion on the work being undertaken by members of groups (WGs, FTs and others), while the Annual Workshop is a combination of working meetings and inspirational discussions and explorative dialogues.
The **EDITS 2023 Annual Meeting** took place between 7-9 November in Lisbon, Portugal, with the participation of around 40% of the EDITS members and a few external participants. The Conference had a specific session dedicated to policy and invited local policy-makers. There was a possibility to join online. [6]

[5] Part 2 of this report presents these meetings in more details.
[6] A report of the Annual Meeting was submitted to RITE and summary of the contents is presented as Annexes 1-3 here.

Building on the current focus areas of EDITS, three key themes were selected:

(1) delivering wellbeing,
(2) connecting with policies, and
(3) cross-sectoral research.

Beyond the Consortium meetings, the EDITS network organized **over 60 specific meetings** in 2023-24, along specific topics, fast-tracks, and Working Groups. These have a multitude of formats (online discussions, in-person working meetings, online writing sessions, data-collection sessions, co-lead coordination meetings, etc.).

PUBLIC OUTREACH AND POLICY INTERACTION

EDITS has a broad range of **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/
- Facebook page: https://www.facebook.com/profile.php?id=100083345312269
- Youtube channel: https://www.youtube.com/@editsnetwork9803

EDITS has focused on public and policy engagement using online and, in-person and hybrid public speeches and seminars:

- We held **three EDITS webinars in the period**, which can be watched on-demand at https://www.youtube.com/@editsnetwork9803 (#3 on 30.03.2023; #4 on 17.05.2023. and #5 on 14.12.2023)[7]
- A **policy conference** was held in the scope of the EDITS Annual Meeting in Sintra, Portugal on 8 November 2023, where Portuguese national and local policy-makers were invited to discuss with EDITS distinguished speakers.
- EDITS organized **one side-event at the COP28** in the Japan Pavilion on 11 December 2023 titled " Demand-side solutions to disruptions "[8].
- EDITS co-organized a **scientific in-person Symposium on 19-20 June 2023 in Oxford, the UK on Technology and Global Change**. The Conference was organized by Charlie Wilson (Oxford), Greg Nemet (Wisconsin)
- **A policy seminar was organized in India in the form of** hybrid seminar in New Delhi, India on 14 December 2023 to engage with Indian policy-makers in relation to low-carbon and socially beneficial futures, titled **"Energy and well-being- The Indian case study"**[9]
- A **scientific conference was organized on 19-20 June 2023 in Oxford, UK** by Charlie Wilson (Oxford) and Greg Nemet (Wisconsin).
- A **scientific seminar "High wellbeing with low energy demand towards modern net-zero cities" was organized by EDITS on 03.11.2023 in Vienna, Austria** in the scope of the International Vienna Energy and Climate Forum.

[7] Specific information and proper links to each webinar are found in Part 5 of this report.
[8] More information is available in Part 5 and at https://iiasa.ac.at/events/dec-2023/edits-at-unfccc-cop28-demand-side-solutions-to-disruptions .
[9] Information about the event can be found in Part 5 of this report and at: https://www.eiee.org/event/edits-webinar/.

PART 2. CAPACITY AND NETWORK

EDITS was launched at the end of 2020 after the inaugural Virtual Dialogue on Energy Demand changes Induced by Technological and Social Innovations. This was followed by annual meetings: in December 2021 in Laxenburg, Austria on "Energy demand changes through innovations"; in August 2022 in Laxenburg, Austria "Transformation to high wellbeing with low energy demand". The last meeting was held in November 2023 in Lisbon, Portugal, with title "Conference on improving wellbeing while avoiding dangerous climate change".

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.

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 largely self-governing**.

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 (RITE), Arnulf Grübler (IIASA), Keywan Riahi (IIASA), Bas van Ruijven (IIASA) and Benigna Boza-Kiss (IIASA).

The organization of the network has a flexible structure (see Figure 2 in the Executive summary), 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. The Plenary can view and comment on research, modeling, and other activities. The Plenary are invited to regular meetings, as well as webinars. The plenary have access to working materials on the shared working space.

- **Regular meetings**

Intellectual and inspirational exchanges are organized in **Quarterly Meetings and an Annual Workshop**. In 2023-24, **three Quarterly meetings (4-5 April, 12-13 June and 26-27 September 2023)** were organized. One **Annual Workshop (7-9 November) was held in Lisbon, Portugal**. The Annual meeting was complemented by a number of side-events, therefore the Community was meeting also on **6th November and 10th November**.

Quarterly 2023/1 was held on 4-5 March (79 participants). The meeting was an opportunity for all WGs to give an update and the fast-track streams that were launched around this time presented their plans.

Quarterly 2023/2, was held on 12-13 June (62 participants). All fast-tracks reported on their progress, and comments were received from the Community. The second session was dedicated to the model complementarity exercise, in particular to data preparation and the use of the scenario database. The topics of the upcoming Annual meeting were also discussed and decided.

Quarterly 2023/3 was held on 26-27 September (64 participants). All fast-tracks reported on their progress, and comments were received from the Community. New fast-track ideas and preparations for the Annual Meeting were also discussed.

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 **over 60 specific meetings** in 2023-24, along specific topics, fast-tracks, and Working Groups. These have a multitude of formats (online discussions, in-person working meetings, online writing sessions, data-collection sessions, co-lead coordination meetings, etc.).

- **Working Groups**

EDITS is organized into **eight working groups (WGs)**., which is reviewed regularly. As a result of the review the WG Wellbeing and fast-tracks were added. The working groups are: WG 1-Buildings, WG 1-Transport, WG 1-Industry, WG 2-Data, WG 3-Narratives, WG 3-Complementarity Protocol, WG 3-Synthesis, and WG 3-Wellbeing. Each Working Group is lead by 2 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 4 in Part 3.

- **Fast-tracks**

Dedicated research is carried out within smaller teams. These can operate within the WGs, or as **fast-track streams** (FT). The fast-track scheme was launched early 2023 to facilitate fast paced, high quality, paper-oriented demand-side research. Fast-tracks are motivated to encourage an increasing amount of innovative, cutting edge, demand-side relevant research, policy-support and communication streams to produce high level outputs within a short timeframe to be conducted by a smaller team within the consortium. The supported topics and resulting fast-track outputs would otherwise fall outside the ongoing structure of the EDITS Working Groups. Every fast-track stream must result in at least one scientific paper, which can be research article, perspective, opinion pieces, or alike. In addition, outputs such as Policy Briefs or White Papers, blog series or podcast series, datasets etc. are also encouraged. Fast-tracks are paid or non-paid activities, and may function as part of a WG or independently. In 2023-24 eight fast-tracks were done, of which six were provided funding from EDITS (Table 2).[10]

Table 2. List of fast-tracks in 2023-24

Fast-track number	Title	Lead name
FT23-1	High well-being with low energy demand: accounting for living standards in buildings modelling for the global south	Souran Chatterjee (University Plymouth) and Alessio Mastrucci (IIASA)
FT23-2	Lower is Securer: Low Energy Demand and Energy Services Security	Nuno Bento (ISCTE) and Benigna Boza-Kiss (IIASA)
FT23-3	How much societal material stocks and resource use are needed to achieve Decent Living Standards and high wellbeing around the world?	Jan Streeck (BOKU)
FT23-4	New metrics to measure and value demand-side services and well-beings	Jingjing Zhang (LBNL) and Joyashree Roy (AIT)
FT23-5	Harnessing sufficiency	Yamina Saheb (Openex)
FT23-6	Crises as opportunities for accelerating the demand side energy transition	Diana Urge-Vorsatz (CEU/BDH), Caroline Zimm (IIASA)
FT23-7	Demand-side data gaps	Leila Niamir (IIASA)
FT23-8	High with Low: Harnessing the Power of Demand-Side Solutions for High Wellbeing with Low Energy and Material Demand	Masahiro Sugiyama (Tokyo University)

EDITS MEMBERSHIP AND COLLABORATION

As of February 2024, the EDITS network has **182 individual members** from **24 countries** (Figure 5) representing **102 Research Teams**. This is almost 20% growth from 154 members in 2023 and 149 in 2022, including a few earlier members leaving EDITS due to e.g. change of workplace. EDITS membership is by invitation only. Members are

[10] More information about the results and activities are reported in Part 3.

proposed by others and they share their data and interest with us via the membership form: https://docs.google.com/forms/d/e/1FAIpQLSfp2Aaa-fAxnK0Ef0inVj6U9RCRvUky4YSmxoqQLsLciwNXlQ/viewform

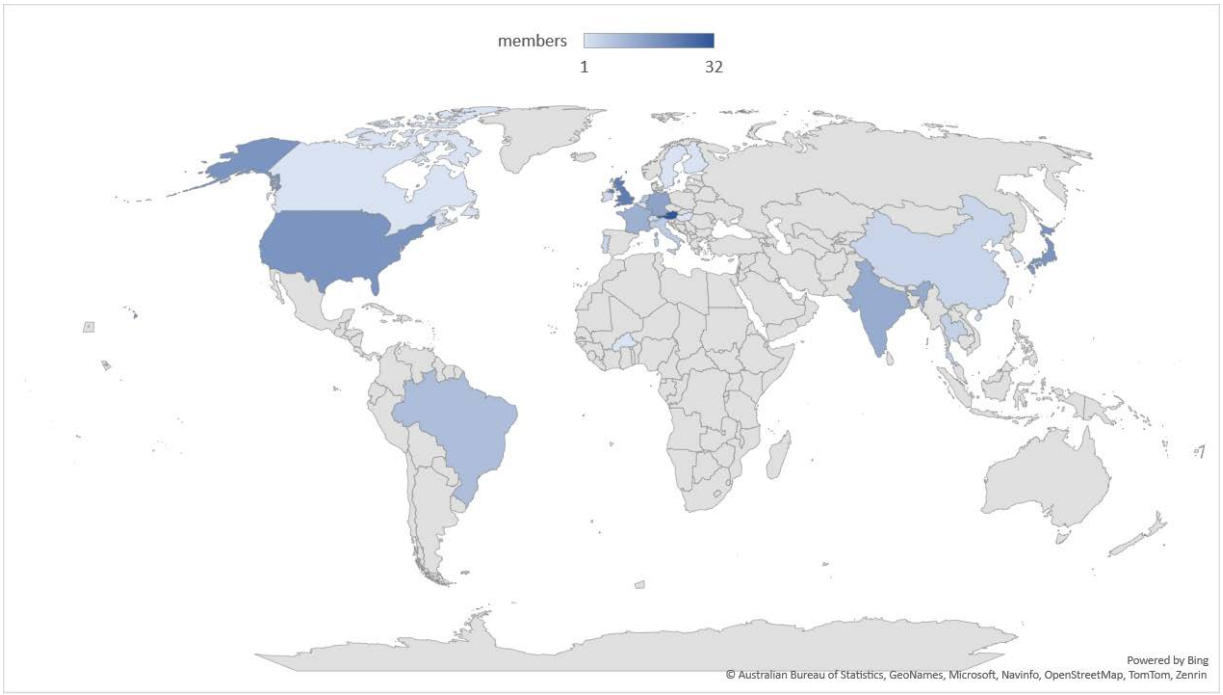

Figure 5. Geographical distribution of EDITS members

EDITS members are offered to choose Working Group membership. **85% of all members take part in at least one Working Group (as growth from 74% in 2022 and 63% in 2021)**, which indicates a higher level commitment than being "only" a plenary member. Figure 3 in the Executive summary illustrates the membership status of each Working Group. Gender (Figure 4) and geographical distributions have improved over the years, e.g. the ratio of females changed from 36% in 2022 to 41% in 2023.

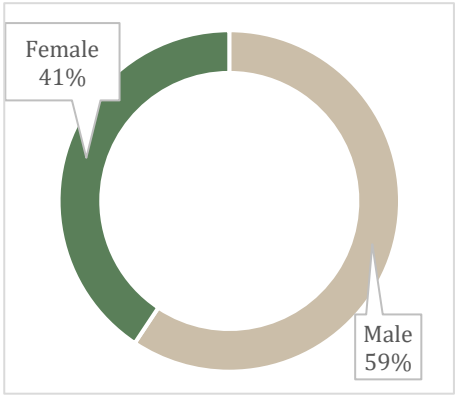

Figure 6. Gender distribution of EDITS members (individuals) as of February 2024.

DEMAND-SIDE MODELS

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.

EDITS has been working with **31 demand models around the world** (Table 3) and was in contact with further 11 models (Table 4). 18 models of the identified 42, have a global coverage or focus, 21 of them are national and 4

multinational and one is at city level. This diversity makes it possible to develop a complementary modelling of different geographical levels and across sectors (Figure 5). The originally associated models were invited to a survey and have been compared in the review papers. Further information can be found in the Sharepoint.

Table 3. Updated list of demand models working with EDITS in 2023-24.

Model name	Host	Host location	coverage
MESSAGE-ACCESS-E-USE	IIASA	Austria	global
MESSAGEix-Buildings (CHILLED/STURM modules)	IIASA	Austria	global
Perspectives on Indian Energy based on Rumi v1.0.0	Prayas	India	India
Sustainable Alternative Futures for India	Center for Study of Science, Technology, and Policy, India	India	India
Total Residential End-use Simulation	Osaka University	Japan	Japan
Urban Building Energy Model for Japanese Commercial Building Stock	Urban Energy System Lab. Osaka University	Japan	Japan
High-efficiency building model 2.0	CEU	Hungary	global
MESSAGEix-transport	IIASA	Austria	global
PASTA	ITF-OECD	France	global
IMAGE-Transport	PBL	Netherlands	global
MESSAGEix-Materials	IIASA	Austria	global
Tsinghua-life cycle analysis model	Tsinghua University	China	China
MISO-model v2	BOKU	Austria	global
Resource Efficiency and Climate Change Mitigation, version 2.4	Freiburg University	Germany	global
Amadeus-ORPHEE	RTE, Economics Power System Division	France	France
Behavioral change in ENergy Consumption of Households Agent-based Model (BENCH) - v.3	IIASA	Austria	European cities
Brazilian Land Use and Energy System (BLUE)	COPPE	Brazil	Brazil
COFFEE	COPPE	Brazil	global
DNE21+	RITE	Japan	Global
BISE	CEU	Hungary	global
Vehicle-Stock-Model	University of Cambridge	UK	UK, China
MAT-dp	University of Cambridge	UK	Africa, Asia
Korea CGE Model	Yonsei University	South Korea	South Korea
Data Center Energy Model	UC Santa Barbara	USA	global
WITCH	RFF-CMCC	Italy	global
UNIfied Climate Options Nexus-Global v1.0.0	Korea Environment Institute	South Korea	South Korea
C3IAM/NET	Beijing Institute of Technology	China	China
LCA model of Iron and steel in China	Tsinghua University	China	China
Chinese buildings model	BERC Buildings Energy Research Center	China	China
SPINE	AIT	Thailand	global

Table 4. Updated list of demand models outside EDITS in 2023-24

Model name	Host	Host location	coverage
MoMo	IEA	France	global
Forecasting Energy Consumption Analysis and Simulation Tool (FORECAST)	Fraunhofer ISI	Germany	selected countries and regions (EU)
EDGE-Buildings 2.0	EIEE	Italy	global
UK National Household Model	UCL	UK	UK
UK MRIO	Centre for Research into Energy Demand Solutions (CREDS)	UK	UK
UK Transport Model	Centre for Research into Energy Demand Solutions (CREDS)	UK	UK
UK Building Model	Centre for Research into Energy Demand Solutions (CREDS)	UK	UK
UK TIMES	Centre for Research into Energy Demand Solutions (CREDS)	UK	UK
US-REGEN	EPRI	US	US
TIMES Austria	Austrian Energy Agency	Austria	Austria
Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA)	JRC, Seville	Spain	EU

The host organizations of the models identified in EDITS are scattered around the globe (Figure 7).

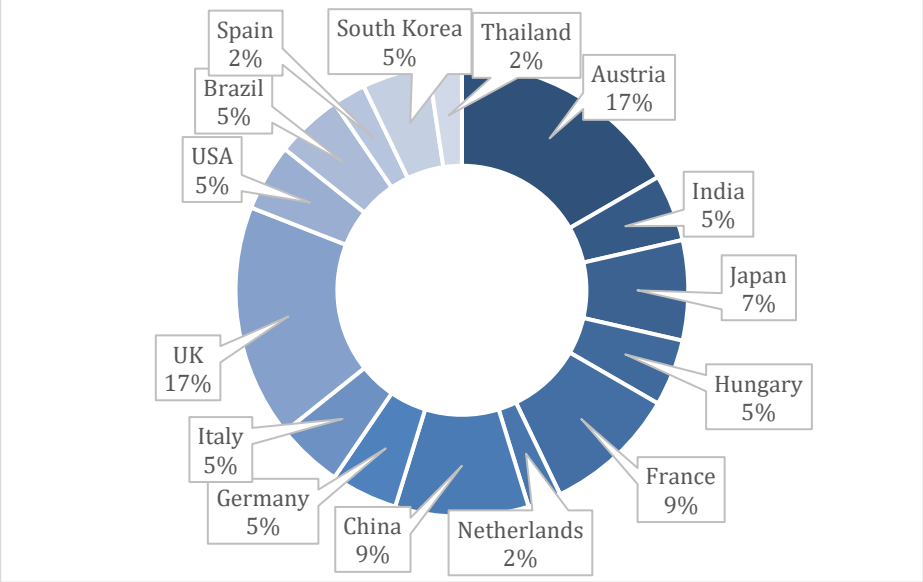

Figure 7. Host countries of the identified models within EDITS in 2023-24.

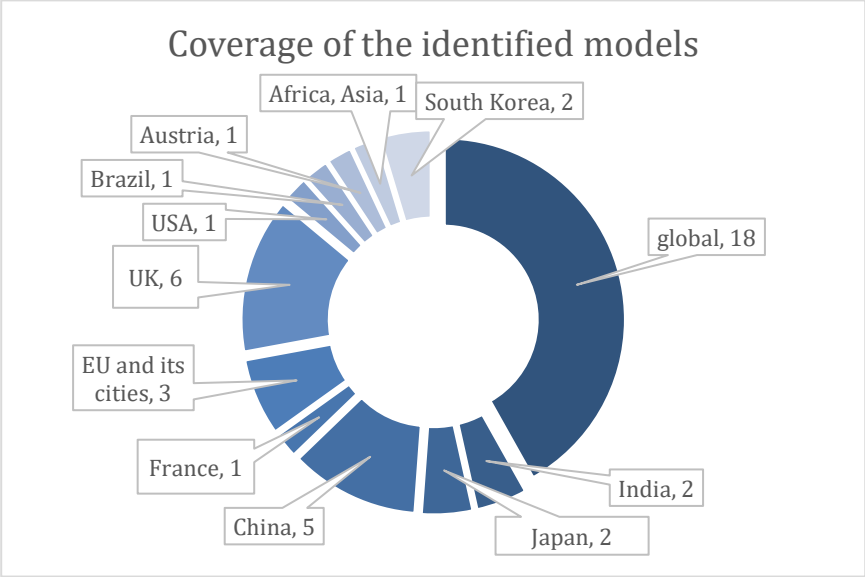

Figure 8. Coverage of the identified models within EDITS in 2023-24.

COMMUNICATION AND 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 4). There is a public email for external interest: edits-public@iiasa.ac.at.

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.

EDITS has a broad range of **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/
- Facebook page: https://www.facebook.com/profile.php?id=100083345312269
- Youtube channel: https://www.youtube.com/@editsnetwork9803

EDITS ANNUAL MEETING 2023

The EDITS Annual Meetings are a fundamental basis for the collaborative research and modeling within the EDITS initiative. The in-person meetings offer a forum for the combination of deep discussions and a place to enhance specific workflows. At the Annual meetings, the personal presence is leveraged by sitting together in small working teams and moving towards scientific outputs, such as scientific papers, policy briefs, communication materials, and even databases.

The EDITS 2023 Annual Meeting (Figure 9) took place between 6-10 November in Lisbon, Portugal, with the participation of around 40% of the EDITS members and a few external scientists. There was a possibility to join online. Building on the current focus areas of EDITS, three key themes were selected to underlie the EDITS Annual 2023:

(1) delivering wellbeing,
(2) connecting with policies, and
(3) cross-sectoral research.

The Annual consisted of various session styles:

a) Plenaries: where a few keynotes were presented to set the stage for the topics (Session 1, Session 6 and Session 8)
b) Discussion sessions framed by different working groups, such as:
    a. Session 2: Discussion about wellbeing and its provision, framed by the wellbeing WG, synthesis WG and narrative WG
    b. Session 4: Discussion about policy enablers and barriers, framed by protocol WG and data WG
    c. Session 5: Discussion about policy input, framed by protocol WG and narrative WG
    d. Session 7: Discussion about cross-sectoral research and modelling, , framed by sectoral WGs, data WG, and protocol WG.
c) Break-out groups enabled deeper and more personal discussions:
    a. Session 2: Special break-out to discuss different sides of wellbeing provision
    b. Session 3: Provided place for the EDITS community to showcase their relevant ideas, research and results. The session invited ideas that could lead to small internal groups to work on selected dedicated topics, to present research that EDITS members carry out either as part or outside of EDITS, and that they thought would be interesting for the Community.
d) The EDITS community was invited to a parallel conference "Sustainability transitions", which provided insights into case studies of low carbon business solutions.

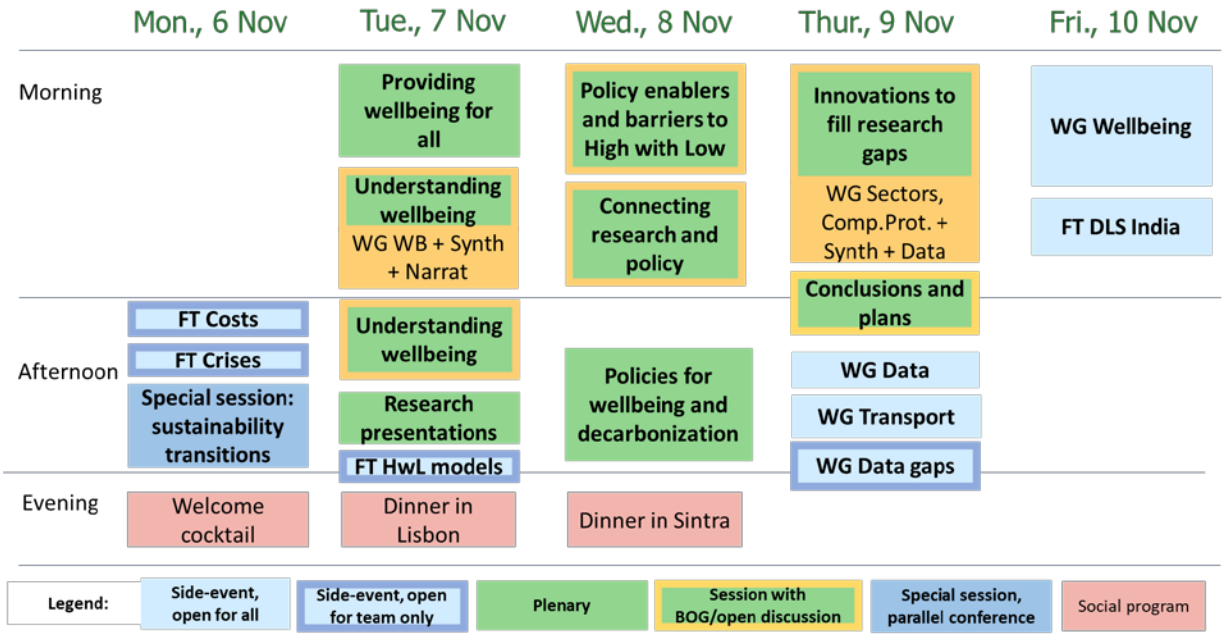

Figure 9. Overview of Annual Conference program

Besides the core program of the EDITS Annual 2023 Conference, writing and working meetings were arranged.

- Certain working groups organized dedicated meeting to progress on their multiannual program, as was the case of WG Data, WG Transport and WG Wellbeing.
- Fast-track streams arranged practical meetings, where they discussed particularities of their submitted papers (FT High-with-Low modelling, FT DLS India and FT Energy Security). Other fast-track streams used their sessions to progress on writing and data collections (FT Costs and potentials, FT Crises, FT Data gaps).

Key figures

The meeting had **70 participants in total from 18 countries** (Japan, the USA, Germany, India, Portugal, France, Austria, the UK, Israel, the Netherlands, Switzerland, Italy, Belgium, Brazil, South Korea, China, Thailand, Hungary), of which **58 participants were present in-person and 12 people joined online**. The attendees comprised individuals from a range of disciplines including modelers, social scientists, economists, and engineers. Participation was based on invitation-only, in order to ensure flowing discussions and an attention to definition of future collaborations.

The EDITS 2023 Annual Conference in numbers:

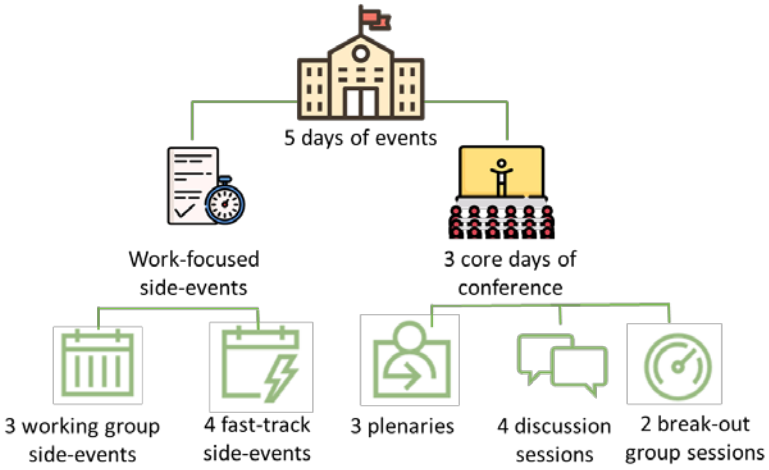

Figure 10. The EDITS 2023 Annual Meeting set-up.

A full summary of the Meeting was submitted to RITE in December 2023, 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.

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** has been done.

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 11).

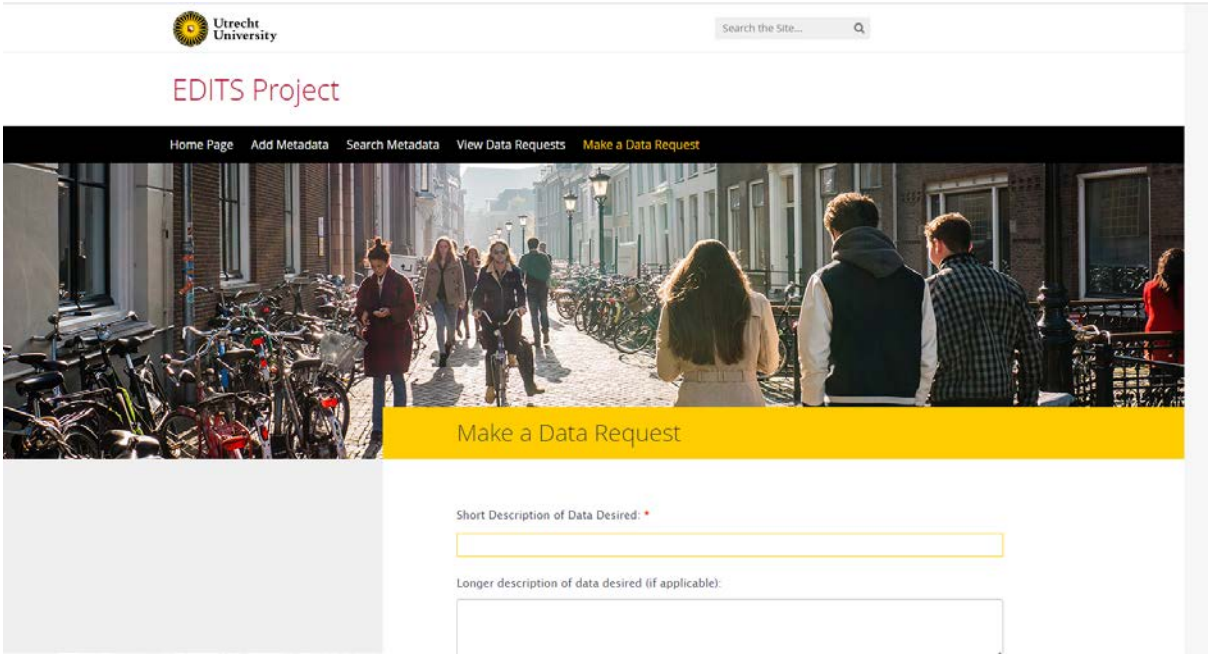

Figure 11. Metadatabase

5) Sector-specific **model mapping for buildings, transport, and industry** has been finished and published or submitted.

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.

7) Fast-track streams have focused on eight specific research topics, which are reported below.

WORKING GROUPS

The actual research and modeling work, i.e. daily activities are organized in Working Groups. The eight Working Groups (WGs) were already presented above in Part 2. Here, a report on their 2023-24 activity is presented (Table 5).

Table 5. EDITS Working Groups in 2023-24

Working Group	Co-lead		Group email address	Main activities in 2023-24
Coordination	Keigo Akimoto	Keywan Riahi	edits@iiasa.ac.at	Oversight of the initiative, coordination across work streams, definition of meeting content, support for data and modeling activities, fast-track motivation, selection and support.
WG 1-Buildings	Alessio Mastrucci	Leila Niamir	edits-buildings@iiasa.ac.at	Finalization of buildings models review. Host buildings sectoral modelling in collaboration with WG Protocol, fast-track on DLE India. Collaborate on data gaps identification and costs and potentials data with fast-tracks.
WG 1-Transport	Paul Kishimoto	Luis Martinez	edits-transport@iiasa.ac.at	Finalization of transport models review. Host transport sectoral modelling in collaboration with WG Protocol. Carrying out transport sectoral modelling. Collaboration with WG data to develop and test the data platform. Collaborate on data gaps identification and costs and potentials data with fast-tracks.
WG 1-Industry	Stefan Pauliuk	Dominik Wiedenhofer	edits-industry@iiasa.ac.at	Finalization of industry models review. Host industry sectoral modelling in collaboration with WG Protocol. Carrying out materials sectoral modelling. Collaborate on data gaps identification and costs and potentials data with fast-tracks. Industry/materials modelling.
WG 2-Data	Oreane Edelenbosch	Nan Zhou	edits-data@iiasa.ac.at	Development of the meta-data platform, testing it with the community for further improvement. Test uploads and working sessions to test use the platform. Hosting the data gaps research to locate and describe data gaps for demand-side. Collaboration with WG Protocol, WG Synthesis and WG Wellbeing on indicators and data. Hosting the fast-track on costs and potentials of demand-side measures.
WG 3-Narratives	Charlie Wilson	Arnulf Grubler	edits-narratives@iiasa.ac.at	Finalization of the High with Low narrative and DETRAS model. Supporting teams with specific understanding of the narrative, e.g. for the fast-track DLE India, WG Wellbeing. Hosting the fast-track on energy security.
WG 3-Complementarity Protocol	Masahiro Sugiyama	Bas van Ruijven	edits-protocol@iiasa.ac.at	After a test modeling complementarity, the protocol was finalized and scenario data collected in several steps. The Tier 1 indicators are collected in the scenario database and have been used for assessment over the year. The fast-track Complementarity protocol development
WG 3-Synthesis	Shonali Pachauri	Massimo Tavoni	edits-synthesis@iiasa.ac.at	The WG developed a set of indicators to analyze model results. Data from the IPCC AR6 database were used to analyze the available scenarios along the indicators. The WG continues to collect the data from new scenarios developed or created in EDITS.
WG 4-Wellbeing	Sascha Nick	Linda Steg	edits-wellbeing@iiasa.ac.at	The WG is a new activity started in 2023. The group identified four main research directions: (1) 1. How to include wellbeing in sectoral models and IAMs?; 2. Evaluate effects of low demand scenarios on wellbeing and acceptance, 3. What is wellbeing (concept/indicators), 4. Secondary analysis of existing consumption and wellbeing data

FAST-TRACK STREAMS

Fast-track streams (FT) were launched early 2023 to facilitate fast paced, high quality, paper-oriented demand-side research. Most dedicated research took place in these teams and have led to a variety of papers, datasets and policy engagements. The list of fast-tracks that operated in 2023-24 are shown in Table 2.

Number	Title	Lead name	**Results and outputs**
FT23-1	High well-being with low energy demand: accounting for living standards in buildings modelling for the global south	Souran Chatterjee (University Plymouth) and Alessio Mastrucci (IIASA)	✓ Paper 1 (methods): submitted, under revision ✓ Paper 2 (scenario): draft ready ✓ Policy workshop done in Dec 2023, streamed as a webinar (av. on-demand)
FT23-2	Lower is Securer: Low Energy Demand and Energy Services Security	Nuno Bento (ISCTE) and Benigna Boza-Kiss (IIASA)	✓ Perspective paper – published 29 Feb. 2024 * Public webinar to be held in June 2024 * Policy meeting at COP28
FT23-3	How much societal material stocks and resource use are needed to achieve Decent Living Standards and high wellbeing around the world?	Jan Streeck (BOKU)	✓ Scientific paper: draft ready
FT23-4	New metrics to measure and value demand-side services and well-beings	Jingjing Zhang (LBNL) and Joyashree Roy (AIT)	✓ Scientific paper: final draft ready ✓ Datasets
FT23-5	Harnessing sufficiency	Yamina Saheb (Openex)	* Scientific paper: draft * Policy brief + public webinar (target May 2024)
FT23-6	Crises as opportunities for accelerating the demand side energy transition	Diana Urge-Vorsatz (CEU/BDH), Caroline Zimm (IIASA)	* Perspective paper: draft
FT23-7	Demand-side data gaps	Leila Niamir (IIASA)	* Scientific paper: draft – mid 2024
FT23-8	High with Low: Harnessing the Power of Demand-Side Solutions for High Wellbeing with Low Energy and Material Demand	Masahiro Sugiyama (Tokyo University)	✓ Perspective paper: published 11. Jan. 2024

Fast-tracks are motivated to encourage an increasing amount of innovative, cutting edge, demand-side relevant research, policy-support and communication streams to produce high level outputs within a short timeframe to be conducted by a smaller team within the consortium. The supported topics and resulting fast-track outputs would otherwise fall outside the ongoing structure of the EDITS Working Groups. Every fast-track stream must result in at least one scientific paper, which can be research article, perspective, opinion pieces, or alike. In addition, outputs such as Policy Briefs or White Papers, blog series or podcast series, datasets etc. are also encouraged.

Based on the success of the fast-tracks in 2023, a new set has been agreed for 2024-25, with titles:

- WELL-with-LOW - Wellbeing Metrics and Assessment of LED-type Policy Options
- Patterns of Diffusion in Social Innovation-s
- Method and Estimation of Cross-sectoral mitigation potential of Demand side solutions
- Decoding decent mobility: Relating needs, infrastructure, and energy use explicitly
- More benefits with lower demand- Quantifying the co-benefits of LED scenarios

PUBLICATIONS

During the period, the Community has **published 24 papers or book chapters with direct acknowledgement of EDITS**. A **further three papers have been submitted** to journals and are under review, and **nine more are in draft status** and will be soon submitted for publication. Three further papers have been published by team members related to demand-side research.

1) Anil, Kumar, Indrait Pal, Joyashree Roy, Nonthakarn Benjachat, and Kittinut Pimpakhun. 2023. “Critical Infrastructure Resilience in Eastern Economic Corridor of Thailand -a Review.” In Multi-Hazard Vulnerability and Resilience Building: Cross Cutting Issues. Amsterdam: Elsevier.

2) Arnz, Marlin, Leonard Göke, Johannes Thema, Frauke Wiese, Niklas Wulff, Mario Kendziorski, Karlo Hainsch, Philipp Blechinger, and Christian Von Hirschhausen. 2024. “Avoid, Shift or Improve Passenger Transport? Impacts on the Energy System.” Energy Strategy Reviews 52 (March): 101302. https://doi.org/10.1016/j.esr.2024.101302.
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4) Bento, Nuno. 2023. “The Potential of Digital Convergence and Sharing of Consumer Goods to Improve Living Conditions and Reduce Emissions.” Environmental Research Letters, October. https://doi.org/10.1088/1748-9326/ad067e.
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These papers include direct reference to EDITS.

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**[11].

A central repository for papers and presentations is created in the online tool **Zotero**, as well as a list is curated on the Sharepoint.

[11] 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. LED representation in building sector modeling tools

Buildings support human activities and wellbeing by providing shelter and services to their users, occupants and owners. Buildings also contribute to economic activities, form urban design, lock-in favourable or harmful solutions. Improving service provision in buildings while reducing energy demands is important for climate mitigation and many UN Sustainable Development Goals (SDGs).

IIASA has worked with EDITS members to deliver various research activities and results to enhance the modeling and conceptual grounding of the low energy demand opportunities in the building sector.

1) Three IIASA colleagues led the assessment of current knowledge and practices of modeling LED scenario elements in the building sector
   The results are published in ARER. A brief summary of the published paper is given here. The full paper can be found at the link.
   List of contributors: 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, and Bas van Ruijven
2) IIASA colleagues co-lead and participate in the fast-track stream "High well-being with low energy demand: accounting for living standards in buildings modelling for the global south"
   The paper is in preparation. A short summary of the draft manuscript is provided here. The full draft is available upon request.
   List of contributors: Alessio Mastrucci (IIASA), Souran Chatterjee (university of Plymouth), Srihari Dukkipati (Prayas), Krithika Ravishankar (CSTEP), Kaveri Ashok (CSTEP), Benigna Boza-Kiss (IIASA), Leila Niamir (IIASA), Poornima Kumar (University of Oxford), Diana Urge-Vorsatz (CEU), Vasilis Daioglou (PBL)
3) IIASA colleague leads and other IIASA colleagues contribute to the research on demand-side data gaps.
   List of contributors: Leila Niamir (IIASA), Benigna Boza-Kiss (IIASA), Alessio Mastrucci (IIASA), Yohei Yamaguchi (Korea), Huzaifa Butt (AIT), Souran Chatterjee

DESCRIBING THE STATE-OF-THE-ART IN MODELING BUILDINGS

The building sector has a significant climate impact, accounting for almost 40% of energy and process-related GHG emissions (Ürge-Vorsatz, et al. 2020). Demand-side mitigation strategies in buildings technically could provide 78% (6.8 GtCO2e) GHG emissions reduction by 2050 (Creutzig, et al. 2021). Computer-based modeling is a powerful tool for scientists and policymakers to investigate trends and changes in building stocks and their energy demand. However, until now, there has been limited effort to model the buildings sector and its dynamics with a comprehensive view on technological and social transformations towards a low energy demand (LED) future (Grubler, et al. 2018). Representing LED scenarios and their complexity requires major shifts in modeling practices, placing energy services in the foreground of the computation, and accounting for bottom-up elements and drivers that are not yet part of most models. These model capacities require significant development, and potential novel approaches to modeling.

In the review paper "Mastrucci, Alessio, Leila Niamir, Benigna Boza-Kiss, Nuno Bento, Dominik Wiedenhofer, Jan Streeck, Shonali Pachauri, et al. 2023. Modeling Low Energy Demand Futures for Buildings: Current State and Research Needs. Annual Review of Environment and Resources 48 (1): 761–92. https://doi.org/10.1146/annurev-environ-112321-102921" the authors give account of how a range of bottom-up building sector modeling tools approach the representation of LED transformations.

We adopt a multimethod approach combining literature review, model survey and comparative analysis, and expert elicitation and appreciation, to tackle the complexity of LED transformations of buildings and their model implementation. We focus on the principal characteristics of LED narratives accounting for three dimensions of

interventions (socio-behavioral, infrastructural and technological) and four megatrends (digitalization, decent living, sharing economy, and circular economy).

We use the narrative literature review techniques to review relevant literature on energy modeling in the buildings sector and LED transformation. We identify about 150 recent journal articles, narrowed down from an initial list of over a thousand publications. We develop a set of criteria to select literature relevant to LED narratives and scenarios modeling. The selected literature spans from regional to global geographical scope, covers both global north and south, and consists of both impact assessment and forward-looking scenario studies using building sector-specific or multisectoral models. We focus specifically on models that are strong in representing the demand-side of the buildings sector and have or foresee running LED scenarios. We conduct a detailed survey and comparative analysis of 17 models representative of diversity across representation and solution algorithms. We use a dedicated questionnaire in combination with interviews with expert modeling teams to investigate the scope, features, and potential of existing models to capture the future dynamics and impacts of LED transformations. Building on the experience of the EDITS (Energy demand changes induced by technological and social innovations) research network, we discuss the results of the literature review and model comparative analysis in a series of expert elicitation workshops to identify modelling gaps, needs, and best practices.

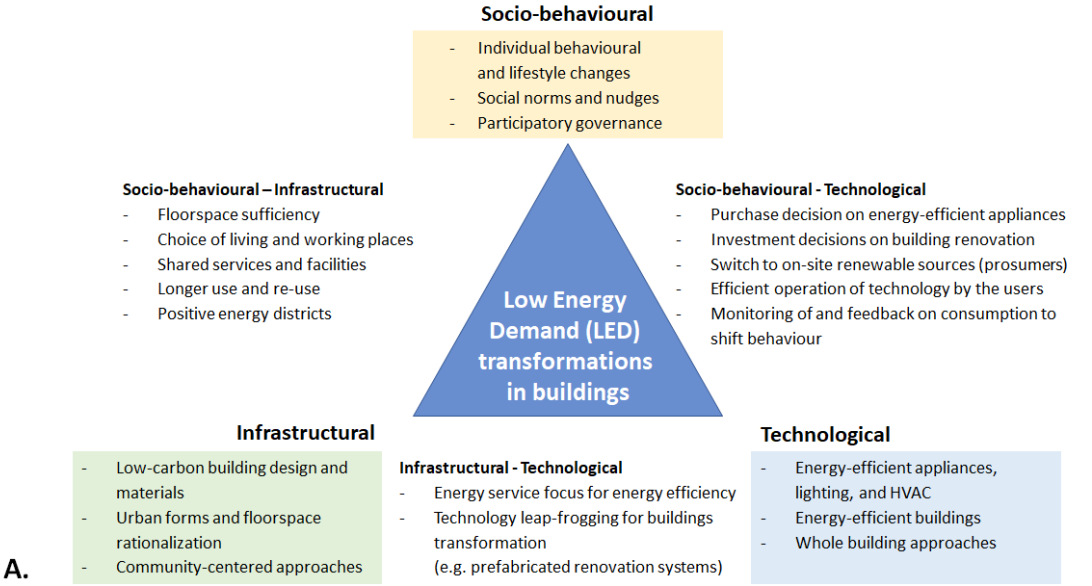
The authors identify best practices and critical gaps in representations of a LED transformation in the building sector. This review provides new insights on the building energy modelling landscape, the developments needed to understand LED transformation, and the linkages with other sectors and multi-sectoral models to better support decision making towards climate change mitigation and sustainability targets.

We categorize the identified models based on their purposes and aims, their methodological approaches, their sub-sector, end-use, geographical, and temporal focus, and level of disaggregation. We claim that diverse types of models are complementary, rather than competitive in their ability and value to represent LED futures in the buildings sector.

We investigate three dimensions of a LED transformation: socio-behavioral, infrastructural and technological interventions (Figure 10). The LED scenario (Grubler, et al. 2018) places radical changes on the energy-demand side as a major driver of mitigating climate change and alleviating social distortions without relying on risky negative emissions in the future (Anderson 2016). The LED narrative focuses on long-term drivers of energy end-use, including higher quality of life, rapid urbanization, novel energy services, diversified end-user roles, and information innovation. For each of the three dimensions of change – socio-behavioural, infrastructural, and technological – we introduce here the rationale, relevance for LED scenarios, and key interventions, and we review existing gaps and best modelling practices.

Socio-behavioral interventions covered in this work include energy-saving practices, behavioral and lifestyle changes. Infrastructural interventions relate to urban design and forms, such as compact cities, and building floorspace reduction. Technological interventions involve net-zero and passive energy building construction and retrofits, smart buildings, energy efficient appliances, dematerialization, and digital convergence. For each of these dimension, we explore trends and strategies towards significant energy demand reductions, informed by experts' knowledge. By reviewing best practices, we identify: a) what kind of LED dynamics are represented in models and how are they implemented?; b) what are the current critical modelling gaps for understanding LED futures?; and c) what key drivers and elements need improved representation?

In addition, we analyze a set of four cross-cutting megatrends driving the LED narrative and so expected to play a key role in energy demand reduction: digitalization, decent living standards, sharing economy, and circular economy. After investigating the connections with the LED interventions above, we focus on best practices and gaps in modeling these megatrends. For digitalization, we include the introduction of building automation systems and smart meters, and work-from-home practices accelerated by the COVID-19 pandemic. We discuss the representation of access to decent living standards (Rao & Min, 2018), in particular access to decent housing and energy. Sharing economy practices addressed in this work include building sharing (e.g., co-housing and co-working), flexible usage, appliances and services sharing. For circular economy, we analyze the representation of building design, materials choices, lifetimes of buildings, refurbish & repair versus demolition.



Low Energy Demand (LED) Transformations

Megatrends / Interventions	Socio-behavioural	Infrastructural	Technological
Digitalisation	Teleworking Smart meters Demand-response	Virtual community approaches Building information modelling 3D printing of buildings	Smart homes and appliances
Sharing economy	Lifestyle changes towards sharing services and facilities	Co-housing and co-working Community-based services	Centralization of equipment Sharing of appliances
Circular economy	Circular practices and changes in behaviours Longer use and re-use of appliances and facilities	Low-carbon design and materials Longer use, re-use and re-purposing of buildings	Low-carbon materials and building systems Lifetime extension
Well-being support			
Decent living standards	Sufficient housing floorspace Adoption of clean technologies	Access to adequate housing	Access to clean and affordable technologies Leap frogging in provision of durable housing

B.

Figure 12. Overview of low energy demand (LED) transformations in buildings. Panel A: examples of LED interventions for each dimension of transformation (triangle corners) and transversal strategies (triangle sides). Panel B: megatrends and relationship with LED transformations.

Key modelling gaps: The analysis of current and emerging building sector modelling practices allowed us to identify key gaps in representing LED transformation, megatrends, and DLS (sections 3,4). Supported by the literature review, model survey results (Figure 3), and expert elicitation process, we here discuss four main areas of critical modelling gaps that need to be addressed by future research, based on four key model characteristics (section 2, Figure 2): spatio-temporal resolution and coverage, granularity, model dynamics, and system boundaries.

Spatio-temporal resolution and coverage: Spatio-temporal resolution and coverage are important aspects of building sector modelling, influencing the ability of representing LED transformations. Geographical resolution in the surveyed models broadly varies from sub-national to national and global. Models with global coverage (*EDGE, HEB, STURM/CHILLED, RECC*) often rely on simplified regional or country representation, depending on available input data. More granular spatial resolution is necessary to further represent LED transformation, including changes in urban form and decentralized service provision, as well as spatial matching of demand-supply to evaluate the transport implications of circularity measures. Coarse aggregation could risk masking aspects related to climate

variability, available fuels, and economics, with higher uncertainty (Chatterjee, Stavrakas, et al. 2022). In terms of geographical coverage, there are still regions not adequately represented in current building sector models. While an increasing number of models focus on developing countries, either from a national (*PIER, SAFARI*) or global perspective *(HEB, ACCESS-E-USE,STURM/CHILLED)*, data gaps still represent a challenge for modelling the building sector and its dynamics in the Global South (Mastrucci et al. 2021), in particularly rural areas, and DLS.

Building sector models used for long-term energy demand scenarios at scales larger than national mostly have annual or multi-annual temporal resolution. Sub-annual timesteps (five minutes to hourly) are already used in several regional and national level models, but are limited in larger scale modelling. Finer temporal resolution is needed to capture seasonal and sub-daily variations and adequately represent LED transformations, including demand-response management and prosumers, behaviour profiles, etc. Combining long term projection of energy demand with finer temporal resolution is challenging due to intensive data and computation requirements and data availability.

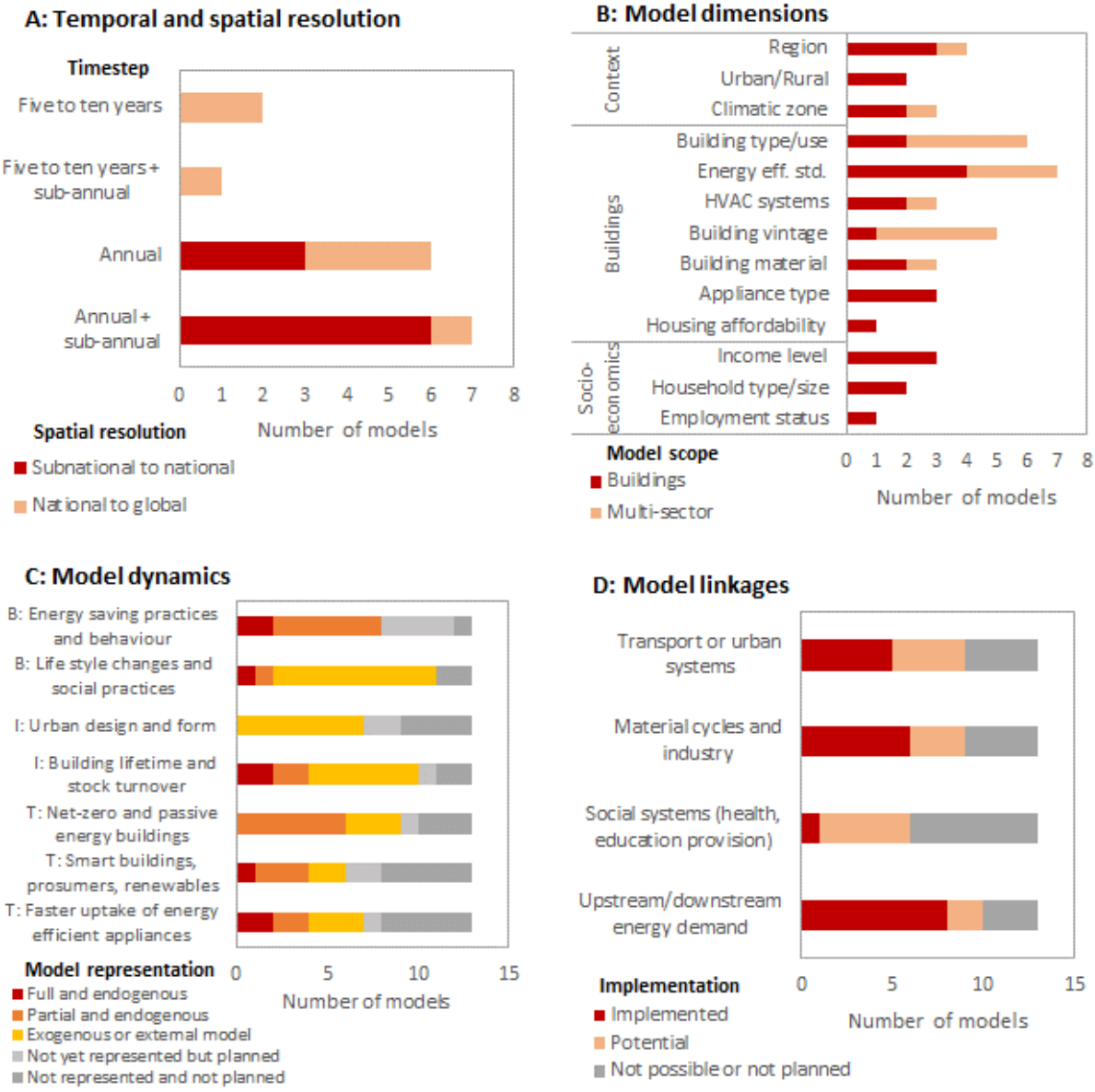


Figure 13 Results for the surveyed models. Panel A: Spatial and temporal resolution. Panel B: Model dimensions considered in buildings and multi-sectoral models. Panel C: Representation of model dynamics related to the three dimensions of low energy demand (LED) transformations (B: socio-behavioural, I: Infrastructural; T: Technological). Panel D: Implementation of cross-sectoral linkages. Note: Results in panel B are based

on 11 survey responses available. Results in panel C and D are based on 13 survey responses received. The underlying data is available in the supplemental material of the published paper, section 2.1.

Granularity: The building sector is characterized by large heterogeneity both in characteristics of the building stock and actors involved in its development and operation. Capturing these dimensions of heterogeneity is critical to represent LED transformations, but challenging due to both data availability and limitations in model granularity.

Potential of representing these heterogeneities is strongly related to modelling approaches, modelling units and granularity, and underlying data structures. Recent model developments have considerably broadened the range of considered dimensions of heterogeneity. Bottom-up engineering approaches typically have more granular representation of building characteristics and technologies, enabling improved representation of heterogeneities in building types, vintage, energy efficiency standards, and technical systems, that are essential for the assessment of technological and infrastructural LED interventions. Other bottom-up approaches, including economic and ABM, have enhanced socioeconomic granularity, necessary to represent different actors of change and household types, that are critical for socio-behavioural LED interventions and megatrends. Accounting for combined buildings, technological and socio-economic heterogeneity is important to further represent distributional aspects key to DLS and other LED megatrends. Gaps persist in representing the socio-economic heterogeneities and actors of change, e.g. individuals, households, businesses, governments, and mapping with infrastructural and technological heterogeneities, for improved accounting of dynamics of transformation and policies effects. Differences also exist between subsectors, with the commercial sector significantly underrepresented compared to residential, and often at a very aggregated level, despite even larger heterogeneities, e.g. in building functions, characteristics, and actors of change.

Model dynamics: Existing building sector models can already account for a number of LED transformations, captured by a series of model dynamics and variables (Figure 11, Panel C). However, model implementations are quite diverse, and often relying on simplified methods or assumptions. Dynamics and variables can be exogenously or endogenously represented, depending on the model research questions and assumptions. Regarding socio-behavioural interventions, most of the surveyed models can represent lifestyle changes, though only partially and mostly using exogenous parameters or via linkage with external models. One key example regards reduction of building size, where changes are commonly represented via exogenous floorspace projections, rather than representing the underlying dynamics. Conversely, energy saving practices and behaviour are covered by a smaller number of models, but mostly endogenously represented. Enhancing the modelling of behavioural aspects could improve the accuracy of modelled energy demands and reduce discrepancies with energy consumption levels observed in the real world (Balaras et al. 2016; Ürge-Vorsatz et al. 2020), especially for low-energy buildings.

Infrastructural changes related to building lifetime and stock turnover, are largely covered, partly represented by dedicated turnover models, but in most cases exogenously assumed. Urban form-related infrastructural interventions are covered by a smaller number of building sector models and only exogenously, for instance by imposing different share of building types in future scenarios. Most models cover technological interventions related to energy-efficient new construction and renovations, either endogenously or exogenously. However, there is a gap in coverage of smart buildings and switch to renewables, as well as technological innovation and business models.

System boundaries: LED transformations are not contained in a certain sector, such as buildings, because LED scenarios incorporate restructuring of servicing systems throughout the entire economy, whereas different sectors are integral parts. Thus, it becomes inevitable to understand and model cross-sectoral linkages (Figure 11, Panel D), in particular with the energy supply systems, industry, and transportation. Linkages with urban systems and social systems are also key and are further reviewed here below. Linking the energy demand- and supply-side is critical for representing LED transformations. Some of the building sector models in this study have been designed to be able to link with large energy system models. For example, *STURM/CHILLED* and *ACCESS-E-USE* are linked with *MESSAGEix-GLOBIOM*, *EDGE* with *IMAGE*, *UK Household Model* with *UK TIMES.* This responds to the demand for a more detailed representation of demand-side strategies in the context of IAM, traditionally focusing more on the supply-side (Edelenbosch et al. 2021).

Assessment of upstream and downstream energy demand and emissions requires improved representation of material cycles and interlinkages with industry. While building sector models have been largely focusing on the operational energy assessment, an increasing number of models consider material aspects. In particular, bottom-up engineering-based models have been increasingly combined with industrial ecology methods, such as life cycle assessment and material flow analysis, to assess all stages of building life cycles, stock turnover dynamics, and material aspects (*EDGE, STURM/CHILLED, EDGE, SAFARI*). Interlinkages with raw material producing sectors (mining, forestry, agriculture) are also very important for LED transformation, and insufficiently considered. For instance, substituting standard construction materials with timber or other renewable resources needs to be assessed carefully vis-a-vis mounting pressures on land systems and trade-offs with food, feed, fuel, natural carbon sinks and biodiversity (Bhan et al. 2021; Haas et al. 2020).

Linkage with urban systems has been partially represented via exogenous floorspace and building type projections, relating to different urban forms. Some multi-sectoral models already incorporate linkages between buildings and transportation, by considering vehicle-to-grid applications (*POTEnCIA*), common behaviour models (*TREES*), and consistent definitions of demand levels across sectors (*SAFARI, RTE model*). This is in line with urban-scale energy modelling, assessing new strategies for urban development planning, energy supply-demand, and distribution network stability (Sola et al. 2020). More fundamental linkages would be required to adequately represent implications of different urban forms on both building and transportation infrastructure and operation, and associated energy and emission, in a more consistent way.

Finally, a clear gap exist in linking building sector models with social systems, including education and health. Most of the surveyed models, except ABM (*BENCH*), currently cannot readily represent such aspects. Linkages between building sector models and approaches offering richer details on socio-behavioural dynamics, e.g. ABM, are currently very limited.

Novelty of this work. Our study discusses critical bottlenecks limiting the development of LED scenarios for the buildings sector, a development that is timely in view of the urban net-zero targets. The innovative contribution of this work is threefold:

- *Low energy demand interventions in the buildings sector:* we identify and expand on the three main types of intervention for transitioning to low energy demand in the buildings sector: 1) socio-behavioral; 2) infrastructure; and 3) technology;
- *Mapping buildings energy demand modeling:* by reviewing literature, surveying models, and conducting interviews, we identify gaps in model coverage, granularity and heterogeneity, model dynamics, and linkages across sectors and models. We identify key model gaps in: the representation of service level provision, the role of buildings as shelter, novel lifestyle and business changes that drive the sector. In addition, for models to provide a comprehensive picture of the whole sector there are gaps in the representation of the non-residential sector, developing countries, linkage between actors, infrastructures and technologies. We show how models alone cannot and should not include all LED aspects, but should be strong in detailed representation of given drivers and form a complete picture via model-interlinkages. We describe this as complementarity.
- *Beyond buildings, cross-sectors and cross-cutting themes:* the domain of this study is not limited to the building stock and dynamics. We go beyond that by studying: 1) the ecosystem and cross-sectors themes, particularly looking to human settlement, urban design, and interlinkages to mobility and transport, and industry; 2) the cross-cutting themes and mega-trends, such as digitalization, decent living standards, and sharing and circular economy.

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HIGH WELL-BEING WITH LOW ENERGY DEMAND: ACCOUNTING FOR LIVING STANDARDS IN BUILDINGS MODELLING FOR THE GLOBAL SOUTH

To reduce emissions trajectory in the Global South, the building sector would play a pivotal role as it globally accounts 30% of final energy use and 26% of energy-related (CO2) emissions in 2022 (IEA 2022). With the increasing rate of urbanization and population growth, the buildings sector's contribution in Global South emissions has been growing (Salam et al. 2020) and is projected to further grow in the future. Results aggregated from bottom-up studies show that the largest mitigation potential for buildings (5.4 GtCO2) will be available in developing countries (IPCC 2023).

Due to increasing affluence, access to appliances and buildings floorspace has been rapidly increasing in the Global South, resulting in higher energy demand per capita (Lamb et al. 2021). However, reducing the energy demand of the building sector blanketly is not advisable as the buildings sector plays an important role in enhancing well-being by fulfilling the fundamental need for shelter and offering services to individuals, communities, and societies at large. As a cornerstone of human existence, shelter is a basic necessity that provides safety, security, and comfort. Proper housing not only shields individuals from the elements but also fosters a sense of belonging and stability, which are integral to overall well-being. In addition, access to basic services such as thermal comfort, clean cooking, refrigeration and labour-saving devices (e.g. washing machines and mixers) is vital to achieving DLS (Demski et al. 2019, Rao and Min 2018).

We focus here on four key DLS-related dimensions of residential buildings: housing, thermal comfort, cooking, and basic appliances. Adequate housing is a key priority to provide safe and sufficient space, and shelter from inclement weather (UN-Habitat 2014). Ensuring basic thermal comfort with modern and clean technologies is crucial to avoid exposure to extreme temperatures and humidity levels, reducing health risks and improving well-being (Mastrucci et al. 2019). Modern clean cooking stoves contribute to better indoor air-quality and reduced health risks and physical work for carrying firewood, that are associated with using traditional biomass (Banerjee 2015). Appliances, including fridges, and televisions, provide important services such as food conservation (fridge) and information (television).

We observed that studies predominantly employ two overarching modeling approaches, namely bottom-up and accounting models, to compute energy demand and DLS measures.

The most widely addressed DLS dimension in these models pertains to housing and thermal comfort. Specifically, approximately 80% of the examined models incorporate these two DLS indicators when calculating energy demand for various end-use building scenarios.

Table 6: List of DLS parameters involved in energy demand models.

Study	Year	Geographical scale	Main method	Domain	DLS dimensions			
					Housing	Thermal comfort	cooking	Appliances
Millward-Hopkins et al. [32]	2020	Global	Bottom-up model	Activity-levels, material requirement or services	✓	✓	✓	✓
Rao et al.[6]	2019	India, Brazil, South Africa	Accounting model	Embodied energy intensities of DLS dimensions	✓	✓	✓	✓
Li et al. [36]	2022	China	multiregional input-output approach	Households energy footprints	✓	×	×	✓
Kikstra et al.[4]	2021	Global	Accounting model	Embodied energy intensities of DLS dimensions	✓	✓	✓	✓
Liaw et al. [37]	2023	Brazil	System dynamics model	Internal room temperature variation	×	✓	×	×
Pereira-Ruchansky, L. and Pérez-Fargallo, A. [38]	2023	Uruguay	Bottom-up simulation (engineering approach)	Buildings structure and energy consumption	×	✓	×	×
De la Paz Pérez, et al. [39]	2023	Cuba	Automated simulation and cost-benefit analysis	Buildings structure and energy consumption	×	✓	×	×
Nutkiewicz, et al. [40]	2022	17 cities in India, Brazil, South Africa, Kenya, Indonesia	Computational energy model	Buildings structure	✓	✓	×	×
Monyei and Adewumi [35]	2017	South Africa	Scenario simulation	Electricity consumption in residential buildings	×	✓	×	✓
Chidebell-Emordi [34]	2015	Nigeria	Analytical and computational energy model	Electricity consumption in residential buildings	✓	×	✓	✓
Schueftan et al. [41]	2016	Chile	Analytical and simulation	Buildings structure and energy consumption	×	✓	✓	×

Estefania, et al. [42]	2023	Ecuador	Simulation	urban and buildings	✓	×	×	✓
Mastrucci and Rao [33]	2018	India			✓	✓	×	×
Flachetta and Mistry [43]	2021	Sub-Saharan Africa	Geospatial energy modelling	Buildings structure and energy consumption	×	✓	×	✓
Wang et al. [44]	2015	China	Numerical and analytical	Buildings structure and energy consumption	✓	✓	×	×

We use a set of multiple models to analyse the trends on access to DLS and energy demands in the residential sector. These six models namely High efficiency building (HEB), Perspectives on Indian Energy based on Rumi (PIER), Sustainable Alternative Futures for India (SAFARI), MESSAGE-Access, MESSAGE_CHILLED-STURM, and Integrated Model to Assess the Global Environment (IMAGE) are selected by circulating an online survey among the "Energy Demand changes Induced by Technological and Social innovations (EDITS)" consortium. These six models are used to to explore how the future energy demand and associated DLS may look like considering the present trend of energy consumption, population growth, GDP, and access to electricity and appliances.

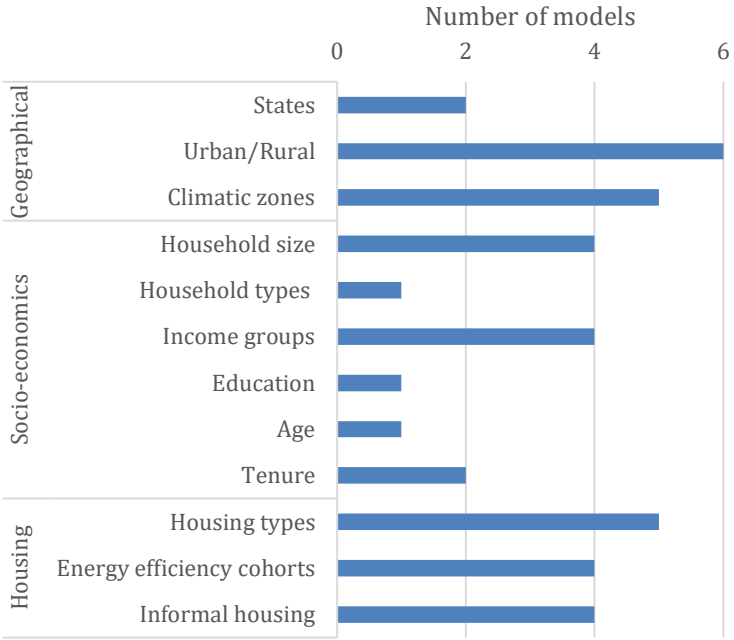

Figure 14: Granularity in different dimensions of the investigated models.

Floor area is a key element for both DLS as well as for energy demand [46,57]. It is essential to know and understand both the present and project future floor area to calculate residential energy demand and also to understand DLS conditions, as shelter being one of the key parameters in the DLS [58]. We use HEB and MESSAGE_CHILLED-STURM models to present the future residential floor area trends based on the present population growth rate and per capita floor area.

The total residential floor area of India is projected to increase by 77% in 2050 compared to 2025 (Figure 13). This increase in floor area is mostly due to increase in urban floor area, precisely around two times which is about 5 billion m2 in 2025b to 15 billion m2 floor area, increase is projected in the urban residential floor area by 2050. Although,

in terms of floor area share, rural floor area has a higher share than the urban floor area, the increase in residential floor mostly expected due to immense increase in urban floor area.

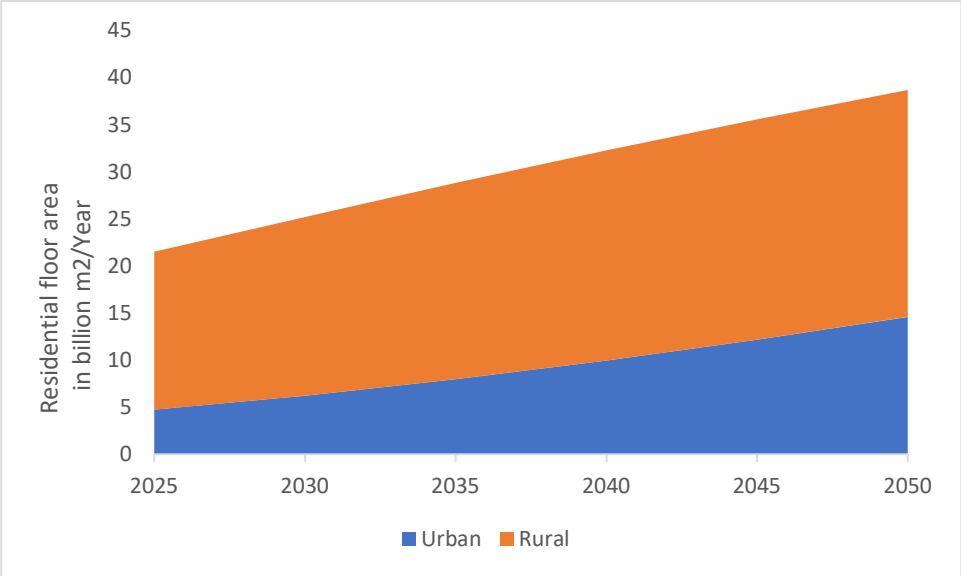

Figure 15: Floor area projection of India under reference scenario of HEB model

However, increasing in future floor area doesn't mean that individual well-being will be improved by having more access to shelter. For instance, although the total residential floor area is projected to increase by 2050, the floor area for informal settlement is also projected to increase by almost 110% by 2050 compared to 2025 (refer to Table 3), and the population living in the informal settlement increases by 94% in 2050 compared to 2015 population. Thus, increase in floor area does not necessarily result in the increase in DLS standards. Furthermore, if we assume that housing for all goal needs to be met, then the total residential floor area increases substantially which may result in substantial increase in the total energy demand as well.

Thermal comfort is a key parameter in determining the total energy demand of the building sector. Unlike the countries in global North, space cooling is the dominating end-use in the building sector in global south countries. Furthermore, thermal comfort is also considered a key component for achieving DLS. The need for cooling to keep people comfortable might be the major recent driver of energy and greenhouse gas emissions as the economies and populations of the world's hottest regions expand and temperatures continue to increase.

In order to represent cooling demand, we use SAFARI and IMAGE models to project the future cooling demand of residential building sector if the present efficiency rate continues. As per the calculations based on SAFARI model, we found if present trend continues, then with the increase of floor area and population, the cooling demand of the residential building sector is expected to grow by almost 800% in 2050 compared 2020 (Figure 14).

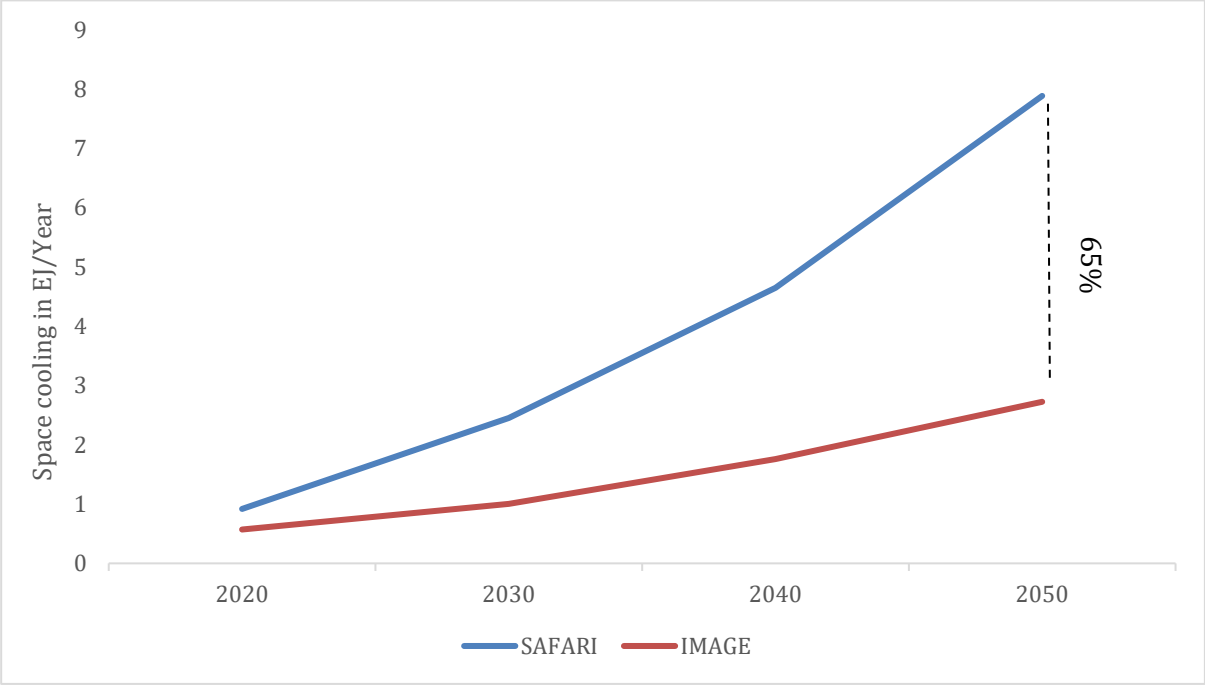

Figure 16: Space cooling under reference scenario in India showing a 65% data range variations in 2050

However, although the cooling demand has showed an upward increase between 400-800% by 2050, considering the present trend, the majority of the people would still not be able to access to residential air conditioning (RAC) by 2050, as shown by the results of the IMAGE model (Figure 15).

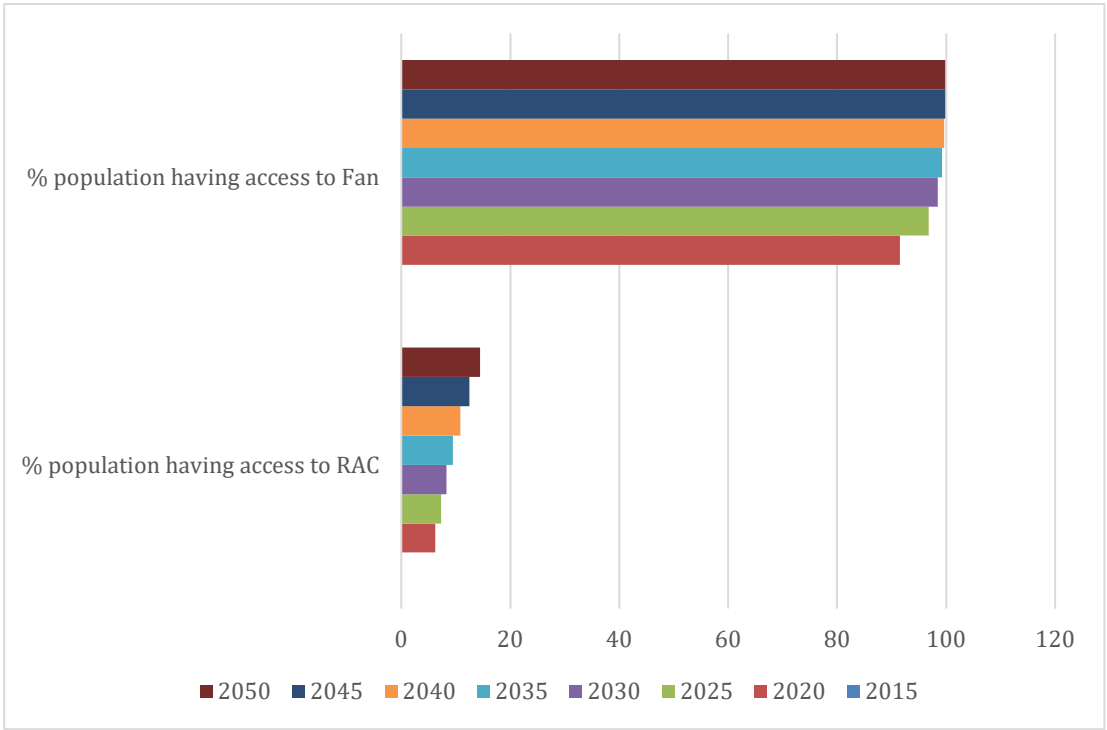

Figure 17: Percentage of the total population in India having access to residential air conditioning and fan

India stands at a crucial juncture where sustainable practices and responsible consumption can significantly influence the trajectory of its future energy demand and well-being. Implementing energy-efficient design principles, adopting high-efficiency building standards, and integrating renewable energy sources are essential steps toward achieving a

balance between providing improved living conditions and minimizing energy consumption. Our research underscores the potential need for India to adopt sustainable and innovative actions that can reconcile these seemingly divergent goals.

With the growing economic growth and population, it is evident that Indian building energy demand would increase substantially, and our models also show the magnitude of this growth. However, empirical evidence from our modelling exercise also suggests that increase in energy demand may not always convert fully to improving DLS indicators. For instance, the cooling energy demand is expected to grow by 400% in 2050, but population who will have access to RAC by 2050 is expected to be around 20% only, which shows a potential inequality, i,e only 20% of the population will contribute 400% increase in the thermal energy demand, while rest of the population will still struggle to maintain the basic thermal comfort level, especially in the absence of strong passive cooling measures. By analysing the data obtained from different models, we have further understood, that a way-out from this inequality and high demand future could be easily avoided if we choose for energy-efficient services over conventional sources of energy. For instance, due to access to clean cooking fuel, despite significant increase in population, Indian residential cooking energy demand would go up to only 8% by 2050, while majority of the population will have access to clean cooking.

Furthermore, the findings of this research provide insights on the data uncertainty and methodological features of different modelling approaches. Different data ranges presented in this study provide emphasis on the need on having a set of coherent scenarios which incorporates both DLS and energy demand together. The reference scenario of this study provides a good basis to develop more modelling evidence by using such coherent scenarios which shows how to achieve high well-being with low energy demand. Furthermore, by discussing the different modelling logics, and methodologies, this study underlines the need to have a coherent database for India which consists of data on all the end-uses as well as the DLS parameter specific data. Without having a coherent database, different models use different databases from various sources and uses different modelling logic which ultimately produces range of outputs. While some models may calibrate to specific data for these energy services, others calibrate to total sectoral energy demand (for instance from IEA statistics for the residential sector) and then estimate the demand for specific energy services in the residential sector. This highlights a clear area for harmonization between models, methods, and datasets.

Nonetheless, through an analysis of using various models, we have highlighted the significance of promoting energy-efficient appliances, and implementing effective policies as pivotal strategies that can contribute to achieving a harmonious convergence of decent living standards and low energy demand. As India continues to strive for economic growth and improved living conditions, the findings of this study show the need for incorporating advanced technologies, and facilitating policy support are indispensable elements in promoting sustainable building practices.

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DATA GAPS REVIEW ALONG THE ASI MINIGATION DIMENSIONS

This study aims to map demand-side mitigation data over sectoral and geographical scales. We focus on Avoid, Shift and Improve (ASI) strategies over end-user sectors. Avoid refers to all mitigation options that reduce energy consumption by individual behavioural and lifestyle changes, as well as through redesigning service provisioning systems; shift refers to the switch to already existing competitive low-carbon technologies and service-provisioning systems; and improve refers to improvements in efficiency in existing technologies where adoption by end users plays an important role. The ASI framework is not well developed yet for the buildings sector, therefore we adopt the following definition: **Avoid**: Sufficiency of final energy and reducing the amount of necessary resources and avoiding need/use of space, appliances, equipment, or other activity levels: this will include but will not be limited to avoiding duplication of space, mixed buildings, small homes, shared offices and appliances, concepts of compact-city. Focus is on lifestyle, building design, size and use (behavioural and lifestyle change), service instead of activity. **Shift**: improve access and switch to renewables in existing and new buildings, as well as in building complexes, districts. Solutions such as community or on-site renewables, micro-grids, switch to lower-carbon fuels and electrification for space heating, cooling, cooking, hot water and electrical uses. Phasing out old technologies and fossil fuels. **Improve**: energy and resource efficiency improvement, such as improved building envelope, improved building technical systems (for heating, ventilation, air conditioning, cooking and electrical uses), smart home and digitalization, efficient appliances, control systems, clean cooking. Focus is on the technology development, roll-out and wider use of existing higher level solutions. Based on the provided definition of ASI measures for buildings, potential mitigations were identified for each category.

We use a systematic literature review method on Scopus and Rayyan to answer the following research questions: To what extent do demand-side mitigation data exist over various geographical scales? Where is the knowledge gap considering sectoral mitigation options and geographical distribution? To what extent demand-data is open access?

We combine systematic literature review and experts' knowledge. The work is carried out in 5 sectors (Buildings, transport, food, industry, urban). The buildings subgroup is headed by Leila Niamir, the research is lead by Benigna Boza-Kiss and supported by Alessio Mastrucci on the IIASA side. Other contributors are Yohei Yamaguchi, Huzaifa Butt, Souran Chatterjee.

A preliminary metadata analysis has been conducted. The mitigation measures for which data are mostly available are technology measures for improve and shift diomensions. Studies that provide data on socio-behavioural and infrastructural solutions are rare, but existent. *Avoid* studies focus on both sociobehavioural and technology. Studies for *avoid* category are 50% fewer than the other two. The share of studies covering avoid, shift and improve is more balanced in the case of *avoid* measures than for *improve* or *shift*. (Figure 16).

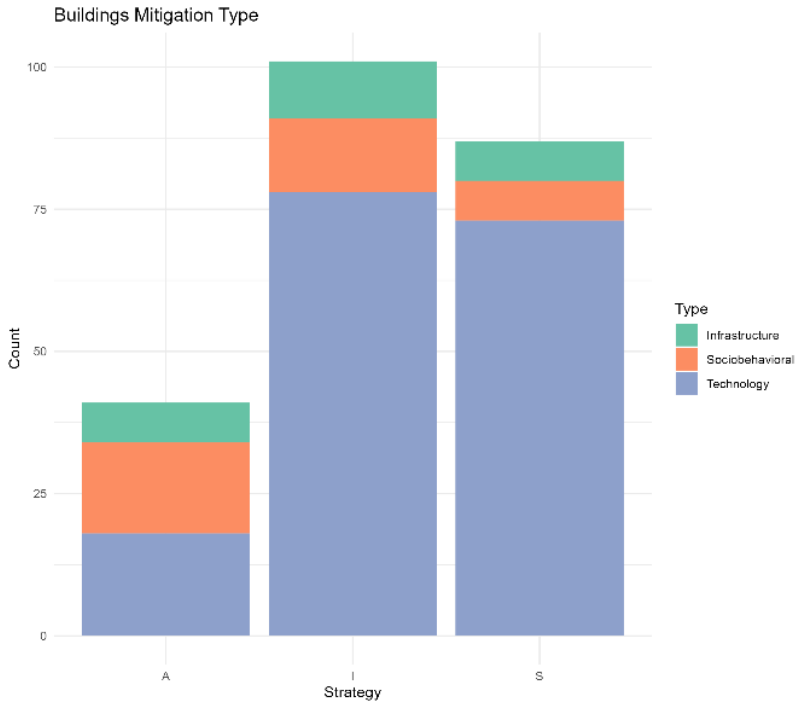


Figure 18. Mitigation type

There is a clear dominance of the energy demand and the GHG emissions data in all three dimensions. Wellbeing data are not available in case of *shift* measures, and relatively small is available for *avoid* and *improve*.

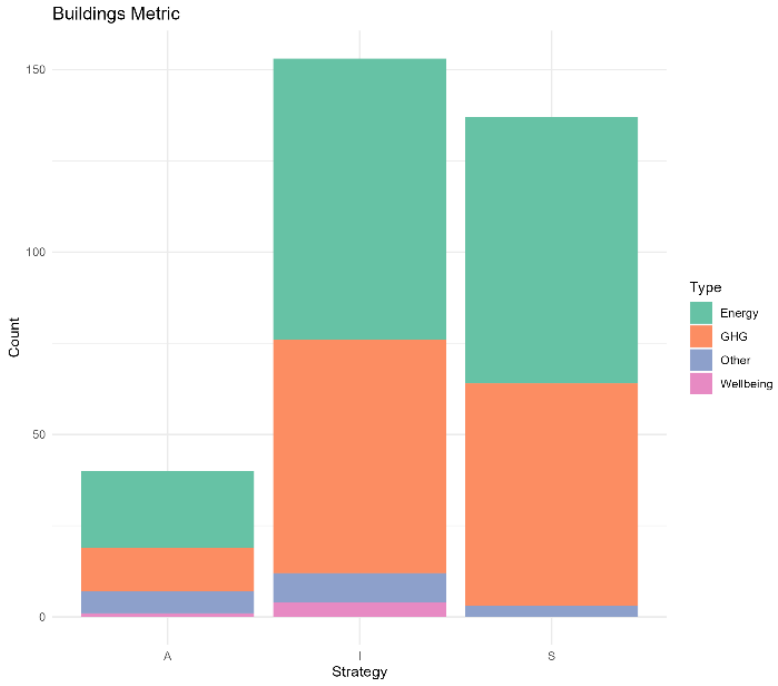


Figure 19. Metrics of the scope of the data

The studies typically include a mixture of datatypes. Modelling data (bottom-up and mathematical models) dominate *improve* and *shift* with census and empirical data following. The types are more balanced spread in the *avoid* dimension. Data on cross-sectoral dimension are mostly missing, but this might be an inherent study-design reason, because we have focused on sector specific data at the rime of the search.

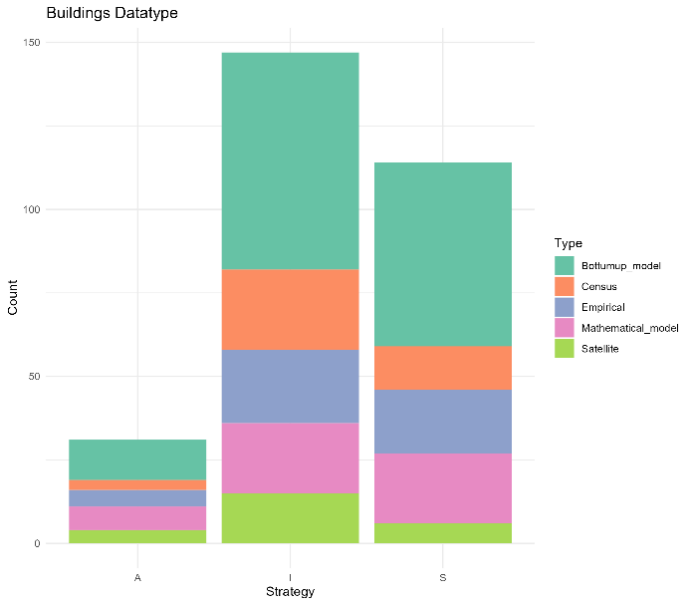


Figure 20. Distribution of studies representing buildings datatypes.

Most studies address local (most) and national scales in all three dimensions. Fewer studies exist with data on regional and global levels.

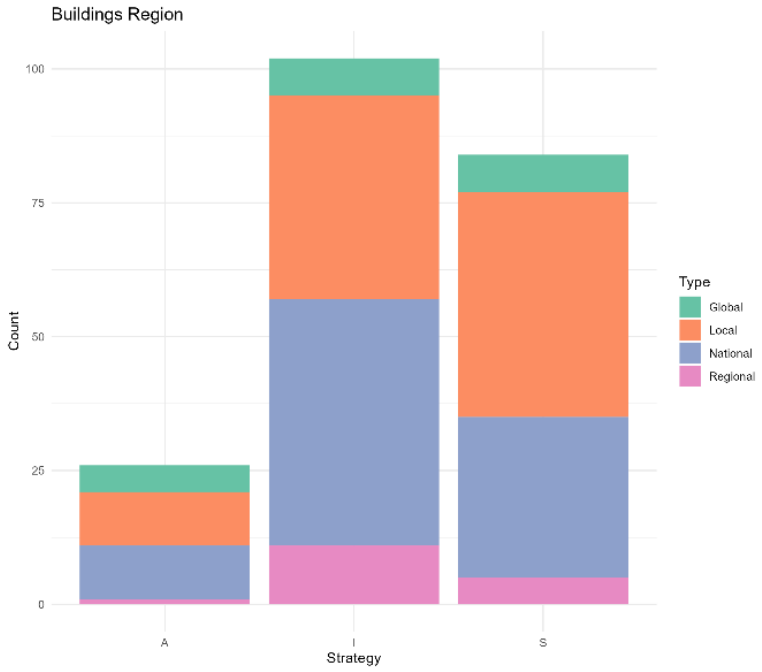


Figure 21. Level of special granularity found in the reviewed studies.

In summary, gaps are still large, especially in terms of studies on socio-behavioral and infrastructure data, at the regional and somewhat at the global levels. In terms of datatypes, satellite data were not used widely, which is probably due to its costs and less advanced development. All in all, avoid type studies are much fewer than the other two. At the same time, studies overlap between the *shift* and *improve* categories.

PART 5. OUTREACH

ONLINE PRESENCE

EDITS has set-up **public channels**: a central webpage (Figure 22): 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/

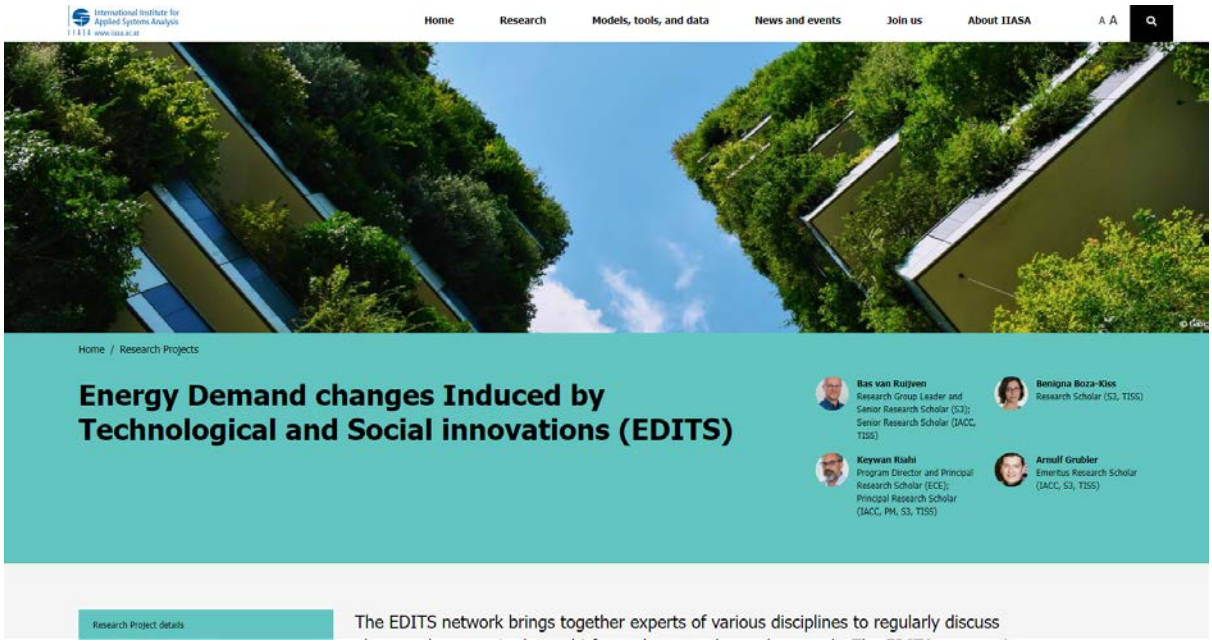
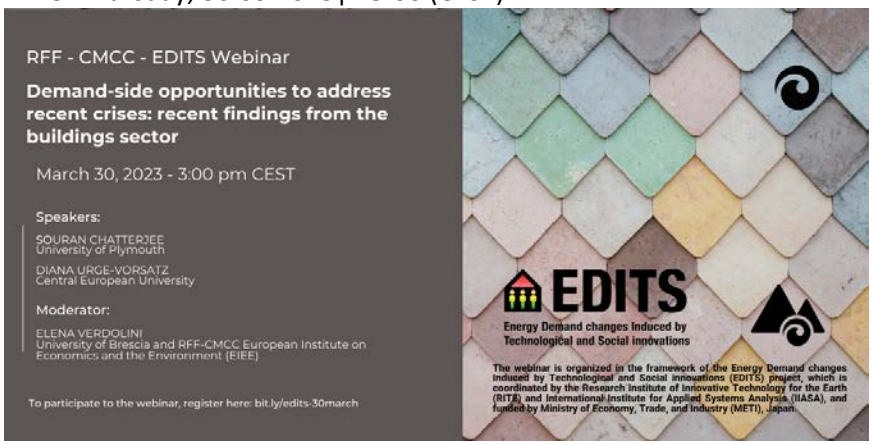


Figure 22. Central webpage

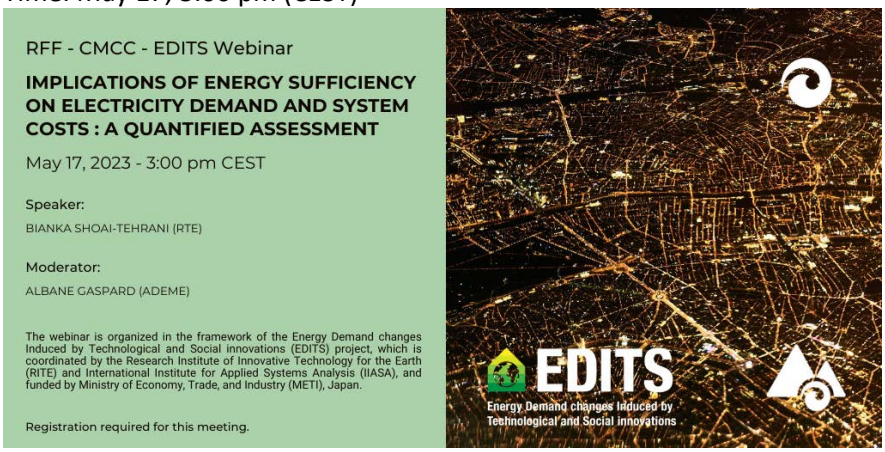
PUBLIC COMMUNICATION: WEBINARS

The Community continued to disseminate results through the established series of webinars, 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 2023 **three EDITS webinars** were held:

- **Webinar #3:** Souran Chatterjee, University of Plymouth, and Diana Urge-Vorsatz, Central European University| Demand-side opportunities to address recent crises: recent findings from the buildings sector | Recording is available at https://youtu.be/-XUiqWEyULc
  Time: Thursday, 30.03.2023| 15:00 (CEST)



- **Webinar #4:** Bianka Shoai-Tehrani, RTE | Implications of Energy Sufficiency on Electricity Demand and System Costs : a Quantified Assessment | Recording is available at https://www.youtube.com/watch?v=-7M3M81Vmls&t=21s
  Time: May 17, 3.00 pm (CEST)



- **Webinar #5:** Souran Chatterjee (Plymouth University), Alessio Mastrucci (IIASA), Ashok Skeevinas (Prayas), Kaveri Ashok (CSTEP), Vassilis Daioglou (PBL) | Energy and wellbeing: The Indian case-study | Recording is available at https://www.youtube.com/watch?v=1IDQGqYndl8&list=PLqj_l70M-izDna_BgeVIkqgQ6ALRFbngX&index=3
  Time: 14.12.2023 | 14.30-16.30 (IST) | 10.00-12.00 pm (CET)

POLICY ENGAGEMENT

Policy session in Sintra, Portugal

A dedicated policy session was held on 8 November 2023 as part of the EDITS Annual Conference. Distinguished invited speakers were:

- **Bruno Parreira, Vice-President of the City of Sintra**
- **Ricardo Paes Mamede, Dean of the School of Applied Digital Technologies, Iscte-Sintra, Portugal**
- **Kenji Yamaji, President of Research Institute of Innovative Technology for the Earth (RITE), Japan**
- **Nebojsa Nakicenovic, Distinguished Emeritus Research Scholar at the International Institute for Applied Systems Analysis (IIASA), Austria**
- **Diana Ürge-Vorsatz, Vice-Chair of the Intergovernmental Panel on Climate Change (IPCC).**
- **Arnulf Grübler, Distinguished Emeritus Research Scholar and founder of EDITS, International Institute for Applied Systems Analysis (IIASA), Austria**

The policy discussion was focused on new trends in industrial policy and climate and sustainability goals. It was agreed that there is (1) Increasing attention to political economy dimensions of green industrial policy. (2) Potential

political conflicts between IP and climate/sustainability goals, esp. in international context. (3) Addressing challenges is necessary at national level and domestically.
It was highlighted that the policy benefits of energy demand measures link well to the integrative policy framework for wellbeing & sustainable development. Demand measures relate to largest spillovers to jobs and to affordability. (plus also resilience and environment). Furthermore, they amplify impacts of specific supply-side policies. Policies can establish the framework in which demand-measures lead to the largest gains, and not having a policy is, in fact, also a policy. Coherence and consistence are important. Until today, demand opportunities are not taken up because they are not visible.

COP28 side-event

EDITS organized a COP28 Side-event at Japan Pavilion, United Nations Climate Change Conference on 11 December 2023. The side event highlighted the need for demand-side solutions more than ever before both because they are the key for resolving the major future challenges but also because of the growing scientific understanding on the way forwrd throgh demand-side solutions. It gathered four eminent researchers from across the world who were also founding organizers of the EDITS initiative.

They included **Keigo Akimoto**, Research Institute of Innovative Technology for the Earth (RITE), Japan; **Nuno Bento,** University Institute of Lisbon (ISCTE-IUL); **Diana Ürge-Vorsatz**, Central European University (CEU), Intergovernmental Panel on Climate Chante (IPCC); **Joyashree Roy**, Asian Institute of Technology (AIT); moderated by **Nebojsa Nakicenovic (Naki)**, International Institute for Applied Systems Analysis (IIASA), Chief Scientific Advisor to the European Commission.

Information about the event can be found at: https://iiasa.ac.at/events/dec-2023/edits-at-unfccc-cop28-demand-side-solutions-to-disruptions

Policy seminar in India

A hybrid seminar was held in New Delhi, India to engage with Indian policy-makers in relation to low-carbon and socially beneficial futures. Improving well-being for all is a prime social target in the Global South and should be prioritized in many ways. The seminar **"Energy and well-being- The Indian case study"** explored the intricate relationship between energy and well-being within the context of India. The meeting was organized by the EDITS consortium under the fast-track scheme, namely the University of Plymouth (UoP, UK), the International Institute for Applied Systems Analysis (IIASA, Austria), Prayas Energy Group (India), The Center for Study of Science, Technology and Policy (CSTEP, India), University of Oxford (UK), Central European University (CEU, Austria), and PBL (Netherlands). The seminar was designed for professionals, policymakers, researchers, and individuals passionate about understanding and contributing to the synergy between energy and well-being in the Indian context.

Information about the event can be found at: https://www.eiee.org/event/edits-webinar/

WIDER SCIENTIFIC ENGAGEMENT

EDITS has started to deliver **presentations and special seminars, side-events at other scientific conferences.**

A **scientific conference was organized on 19-20 June 2023 in Oxford, UK** by Charlie Wilson (Oxford) and Greg Nemet (Wisconsin). The Oxford Symposium on Technology and Global Change was attended by 32 scholars in the field. The symposium at Oxford University brought together researchers working on innovation and technological change applicable to global climate, energy, and other sustainable development challenges. The symposium was linked to a focus issue of the journal Environmental Research Letters on technology and global change and coincided with the 25th anniversary of the publication of the book, Technology and Global Change, by Arnulf Grübler.

A **scientific seminar "High wellbeing with low energy demand towards modern net-zero cities" was organized by EDITS on 03.11.2023 in Vienna, Austria** in the scope of the International Vienna Energy and Climate Forum as a solutions platform to accelerate low-emission, climate-resilient development around the world. The Forum highlighted the action-oriented steps required to achieve the Sustainable Development Goals by 2030, helping to

forge an inclusive pathway that leaves no one behind. The solutions platform facilitateed multi-sectoral, multi-stakeholder, and inter-disciplinary dialogue to advance sustainable energy development while promoting inclusiveness and the empowerment of women and youth engagement. The Forum hosted in-depth solution sessions on the topics relevant to its five themes.

PART 6. Outlook for 2024-25

EDITS has been steering its activities and working methods along the years in order to match the final goals of the initiative and of the members as individuals. The coordinators ensure that there is enough opportunity to influence the initiative and provide comments. In the last year, input and comments were collected at:

- Coordination meeting on 31.08.2023.
- The EDITS Annual Meeting in 7-9 November, at a dedicated
- The Quarterlies
- Meeting with WG Co-leads on 29. February 2024

During these meetings key challenges were identified:

- Limitation on capacities of the Working Group co-leads as well as of the members. Many EDITS participants are heavily involved in a number of working streams (e.g. fast-tracks, review papers, database development, etc.) under EDITS scope. Therefore, starting new activities, or scheduling more meetings is often limited by availability of the potential participants.
- In spite of the capacity issues, there is high interest by members, topics emerge fast and attract interest.
- EDITS has completed a round of stocktaking in many areas, and research and other activities based on them is starting, which transition requires new commitments. We can build on the work done on:
    - Review of models in Sector WGs
    - Demand modeling stocktaking
    - Data and data gap identification
    - Synthesis framework developed
    - Wellbeing conceptual framework developed
    - High with Low narrative has been created, linked to DETRAS
    - Specific fast-track results
- Structures have been established, but they are hard to fill up
    - MCE Protocol - now there is a need for models to develop scenarios
    - Scenario explorer set-up - now there is a need to upload scenarios (existing and new ones)
    - Data Platform: a site hosted by Utrecht University: https://edits-project.sites.uu.nl

Research content and focus:

1. There is interest in moving on from historical adoption of technologies, to instead historical adoption of behaviours. It would be interesting to show how attitudes and behaviours can change, including attitudes, behaviours, social innovation.
2. It is important that conceptual ideas to be linked to concrete modeling. Suggestion to consider realism of interpretations of scenario narratives in models, this helps to have acceptance with policymakers. In Japan and Korea sufficiency ideas are socially acceptable. There is a great improvement in understanding of sufficiency within EDITS.
3. We need to be able to quantify wellbeing, connect with an economic community. HwL seems a solution to many problems facing the world—can we sell it under this heading.
4. There is still a lot to do to connect outcomes to wellbeing indicators, which could be a focus. May want to go deeper in granularity and heterogeneity.
5. More local case-studies are needed. In the policy communication realm, need a narrative framework that goes beyond “supply vs. demand”. Equity within-countries is a main benefit/selling-point.

Structure and working methods:

1. The revised structure works well, though a redesign of Working Groups is necessary. This has been started and WGs will redefine their content and working methods.
2. WGs to operate as a platform for ideas. They will organize discussions including internal and external invited speakers to focus on given WG relevant topics

3. WG collabroation to be established to enhance the MCE work, in particular WG1 sectors will work closely with WG Protocol and identify a few focused modeling topics that make the scenario development/collection easier. Such a focus could include regional focus and/or sectoral focus (for example the DLE India FT is a success story)
4. Cross-WG topics will be incorporated into the WG work. Such topics could be: cross-sectoral or transformation themes, such as digitalization
5. EDITS has become a relatively established community after a few years, and new interest finds us. The community is very Global North oriented and European; needs to be more representative to communicate widely.
6. Bridging with other communities (political scientists, policy-makers, social scientists, business LED representatives) will be needed.
7. The community calls for a working group on communication of narratives. However, this has not been approved by the coordination and co-leads of WGs.

Outreach and policy impacts:

1. There needs to be work done in connecting work with policies, policy-makers, business examples. Each working group should keep this in mind. EDITS and its WGs identify the goals and a roadmap to get there. Alternatively policy analysis that is interesting for policy-makers could be done.
2. EDITS is moving towards being more action-oriented, things are moving forward. It is time that we communicate towards the outside about demand-side measures, invest in communications. There are key selling points: COP27 India launched a "life mission", changing lifestyles for environment; great overlap.
3. In order to reach out and talk to the rest of the world, we should find ways to connect the academic findings and policy-relevance, need clear target to communicate, maybe need a vehicle to tell the story, a way to address the political-economic factors.
4. Conceptual framework emerging for wellbeing. But others like sufficiency maybe not well-received outside this room. Examples in SF Bay area per zoning reform that are tied to sufficiency but framed in a different way. How do we identify these accessible & feasible actions? We have collected good insights from understanding of wellbeing, but still questions about how to define in different contexts and countries. How to connect with external stakeholders, esp. policymakers? There are other, competing issues, e.g. housing crises, energy access, etc.
5. Many outputs ready for communication; others not ready yet.

ANNEX 1: EDITS ANNUAL CONFERENCE SUMMARY

Conference on improving wellbeing while avoiding dangerous climate change
7-9 November 2023
with side-events on 6 November and 10 November
Lisbon, Portugal

CONFERENCE REPORT

Summary of the conference and key take-aways

Brief summary of the core part of the conference is provided. This includes the main sessions and break-out groups of the 3 main days of the conference.
A review of the side-events is provided in the next section of the report.

Session 1. and Session 2. Providing wellbeing for all

The conference was opened by EDITS coordinators, **Keigo Akimoto**, Research Institute of Innovative Technology for the Earth (RITE), Japan and **Bas van Ruijven**, International Institute for Applied Systems Analysis (IIASA), Austria. They summarized the strategic goals of EDITS as:

- Better metrics to measure human wellbeing,
- Evaluate climate implications of digital economy,
- Scenario modeling,
- Dynamic modeling of systems interaction.

The host of the EDITS Annual Conference 2023, **Nuno Bento**, University Institute of Lisbon (Iscte), Portugal opened the Conference with warm words. He welcomed participants and explained the relevance of demand-side solutions in a country like Portugal, where many social problems, such as energy poverty could be mitigated by actions on the demand-side.
The first two sessions were dedicated to a review of conceptual understanding of wellbeing from an energy and material provision perspective, and to how the High with Low narrative and related scenarios with demand-side approach need to encapsulate it.
Session 1. consisted of five keynote speeches. **Shonali Pachauri**, International Institute for Applied Systems Analysis (IIASA), Austria focused on just transition, well-being, and climate scenarios. She presented a comprehensive framework for just transitions, emphasizing justice dimensions and metrics like utility and well-being. The importance of collective responsibility and interconnectedness in global actions was highlighted.

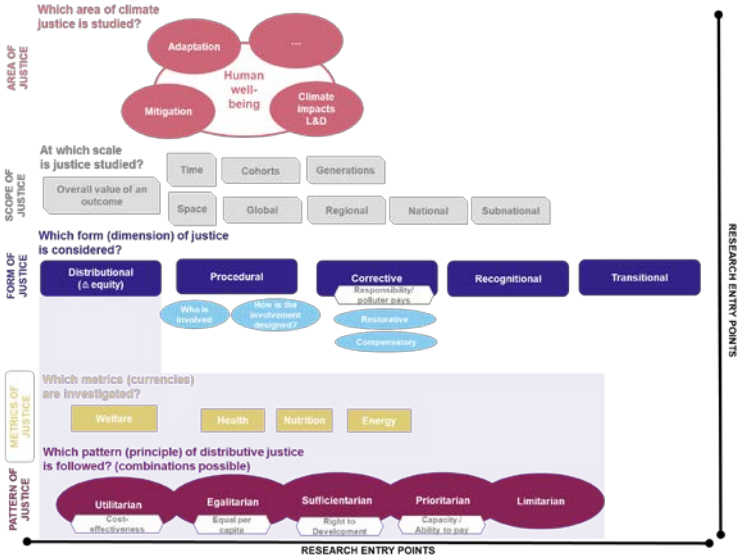


Figure 23. A new justice framework. Zimm et al 2023 (accepted in Nature Climate Change)

Joyashree Roy, Asian Institute of Technology (AIT), Thailand and India explored the importance of wellbeing in the Global South, investigating energy use thresholds and supply-demand framings. When using indicators of 9 metrics of wellbeing and their relationships with per capita energy use using global datasets, with which controlling for country differences, results indicated a plateau in wellbeing metrics beyond a certain energy use threshold. All 9 metrics rise steeply, then attains a plateau at an average annual primary annual energy use of ≤75 GJ per person, a sufficiency threshold, beyond which higher energy consuming countries show little increase in performance. This indicates that distributed equitably, 2015's average global energy consumption of 83 GJ/person (energy sufficiency threshold) could, in principle, allow everyone on Earth to realize 95% or more of maximum performance across all metrics. Globally, this satisfaction of individual wellbeing would lead to energy consumption of 606 EJ, which was the level in 2015 (EIA 2017).

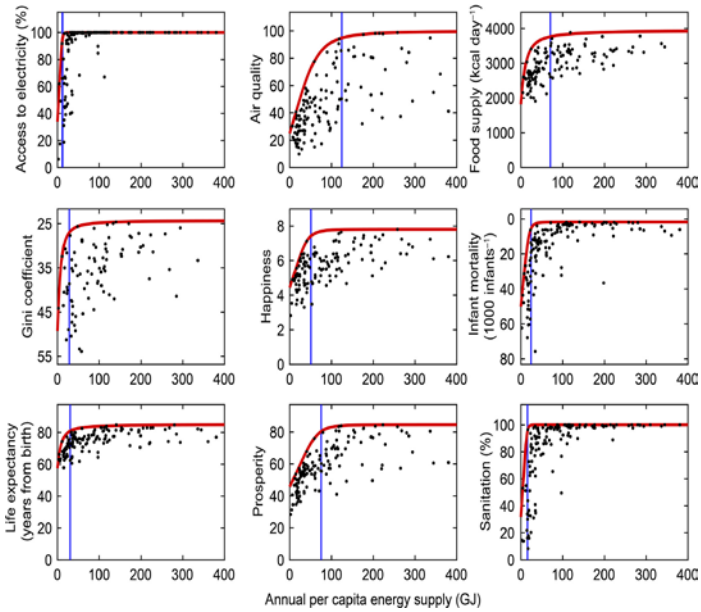


Figure 24. Human wellbeing and per capita energy use. Source: Ecosphere, Volume: 13, Issue: 4, 2022, DOI: (10.1002/ecs2.3978)

Individual countries have a relative performance resulting in (a) "performance deficit," which is the difference between the observed and maximum or target metric value for a given per capita energy use (i.e., the vertical distance below the maximum curve), or (b) "energy intensity inefficiency," the difference between the measured and minimum per capita energy needed to obtain a given outcome (the horizontal distance from the curve to a country's observed. Reduced per capita energy consumption in principle could occur in many higher energy-consuming countries with little or no loss in health, happiness, or other outcomes, reducing the need for global energy infrastructure and increasing global equity.

Massimo Tavoni, CMCC and Politecnico di Milano, Italy discussed multidimensional welfare indices in IPCC AR6 scenarios, addressing within-country inequality and the trade-off between short-term redistribution and long-term welfare. Staying below 2°C only partly limits increase in inequality. Redistributive schemes can revert this, e.g. ca. 2.5% of GDP transfers would be sufficient, which is sizable, but not impossible with clear policy support, to compensate the trade-off between support and welfare.

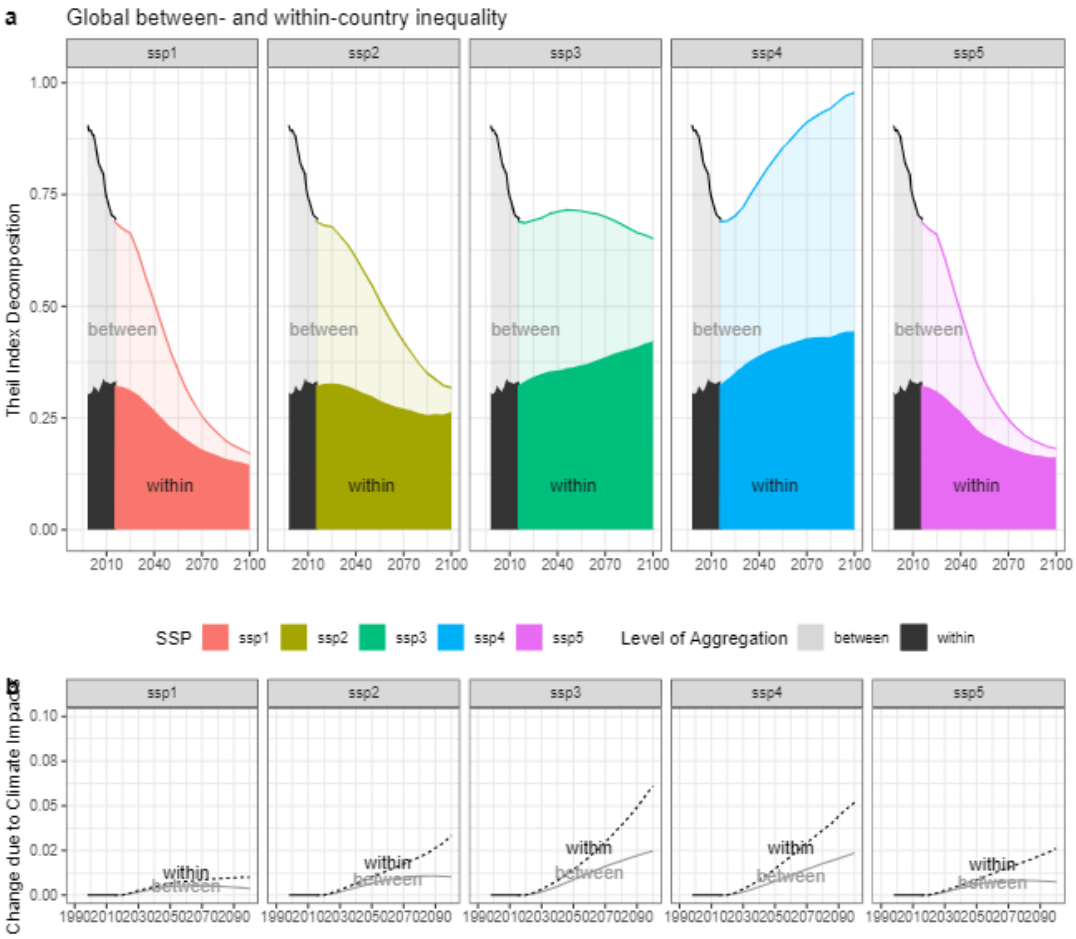


Figure 25. Projected inequalities and how climate change impacts exacerbate inequality. Source: Emmerling, Andreoni and Tavoni, "Global inequality consequences of climate policies when accounting for avoided climate impacts" in press

Sascha Nick, Laboratory of Environmental and Urban Economics (EPFL), Switzerland presented the SWICE project, proposing a systems approach to sufficiency, wellbeing, and transition in the Swiss habitat. In Swiss buildings, energy use has reduced by 33% in the past 31 years, and emissions per square meter have decreased by 2/3. However, square meters have increased by 50%. To address these challenges, action levels and high-leverage points, including mindset shifts, are necessary for system solutions. Well-being precondition includes satisfying all needs, sufficiency as a societal principle, not just individual or behavioural choices. Comfort is an example of how different disciplines define it in various ways. In the context of human needs, comfort is considered a satisfier. Shared spaces, which may serve multiple purposes like kitchens and guest rooms, are also seen as satisfiers. Increasing the size of shared spaces allows for a significant reduction in private space requirements, potentially from 73 to 34 square meters, although this is still far from the aim of 14 square meters. The approach is an adaptation of sufficiency based on the order of satisfiers, where changing how sufficiency is approached has a more substantial impact.

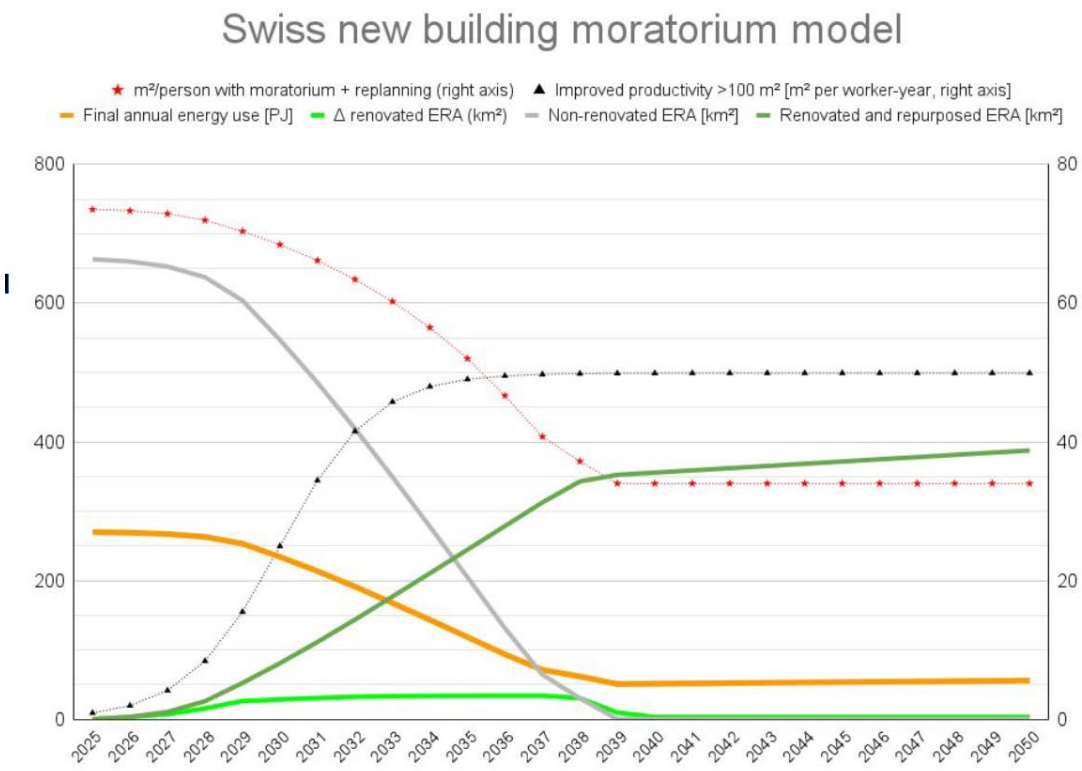


Figure 26. The development of the Swiss housing stock.

Anne van Valkengoed, University of Groningen, the Netherlands examined the impact of low-carbon scenarios on perceived quality of life. She explained that subjective well-being is relevant due to its connection to acceptability and feasibility, including various dimensions like socio-cultural factors. Resistance in society against climate policy can hinder its implementation. She showed an example, "the Dutch climate movie," depicting life in the Netherlands in 2040. The movie portrays changes like smaller houses, plant-based diets, reduced working hours, and more. This video was used to explain the scenarios and their societal consequences, aiding communication with participants. The study involved three samples: 1st-year Dutch psychology students (235), bachelor students in economics (60), and members of the Dutch general public (250). Overall, people had a positive response to the scenarios. Acceptability was explored, with most participants in the general public being slightly to moderately positive, and some having a slightly negative viewpoint.

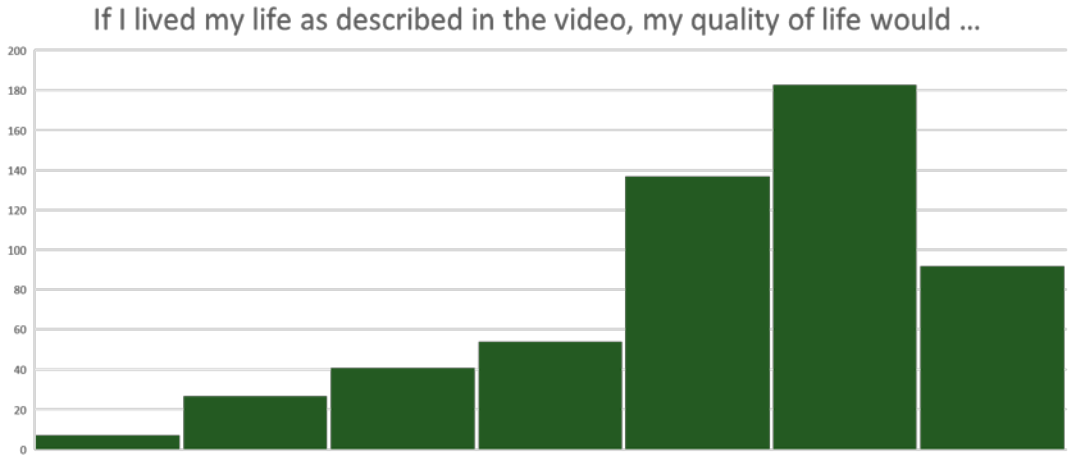


Figure 27. How do people think the scenario would affect their Quality of Life?

After the presentations the audience discussed how people's perceptions change post-implementation, and whether focus should be on the few enablers. E.g. once introduced, people accept the changes, such as congestion charges in

big cities. Therefore , policymakers should not let themselves be hindered by the assumption of non-acceptance. Communication matters.
Overall, the session provided valuable insights into justice, wellbeing, and sustainable transitions, with a call for multidimensional approaches and continued research.

Session 1 was continued in Session 2, aimed at "Understanding wellbeing".
Sascha Nick, Laboratory of Environmental and Urban Economics (EPFL), Switzerland and ***Elina Brutschin***, International Institute for Applied Systems Analysis (IIASA), Austria described sustainable wellbeing within planetary boundaries, presenting various preceding concepts that all explore universal needs, context-specific satisfiers, and societal influences on wealth, these include: Doyal & Gough (1991), Max-Neef's matrix of needs and satisfiers, Di Giulio & Defila (2020), Lamb & Steinberger (2017) and O'Neill et al (2018) "LiLi". A variety of models are available, including bottom-up sectoral models that facilitate learning about different provisioning systems and resource connections. Observations from different models help assess whether needs are satisfied, considering both model input and output. Well-being indicators encompass both objective and subjective aspects. Emmerling's work, linking empirical analysis of the connections between objective and subjective indicators and projecting them into the future, contributes to our understanding of subjective and objective well-being.
They proposed the following all-encompassing definitions:

1. Wellbeing is the result of satisfying needs in all major human needs approaches.
2. Needs are universal, constant over time and cultures, classifiable, non-substitutable, and satiable.
3. Satisfiers, separate from needs, are culturally specific but have common characteristics. Resource need strongly depends on the dominant satisfiers.
4. Desires, potentially infinite, often disconnected from needs, are not useful in planning for wellbeing.
5. Multidimensional needs satisfaction is a necessary condition for and strongly correlates with wellbeing (O'Neill et al 2018, Helliwell 2008).
6. Decent Living Standards (DLS) approach shows that all material prerequisites for wellbeing can be satisfied with 10% of final energy used in rich countries today, while providing wellbeing for all.
7. Significant gaps in providing shelter, nutrition, health, mobility, and socialization remain in all world regions. Closing all DLS material provisioning gaps requires new infrastructure which could be built with a one-time investment of 290 EJ, or 9 months of world's final energy use (Kikstra et al 2021).
8. Provisioning factors strongly affect the effectiveness of satisfier provision: positively (public service, public health, clean energy access, democracy, equality) or negatively (extractivism, economic growth) (Vogel et al 2021)

Building on suggestions made by others, there's a call for a more systematic approach that bridges sectoral and global aspects. It aims to expand the context-specific view of need satisfiers and promote a more holistic approach to need satisfaction.

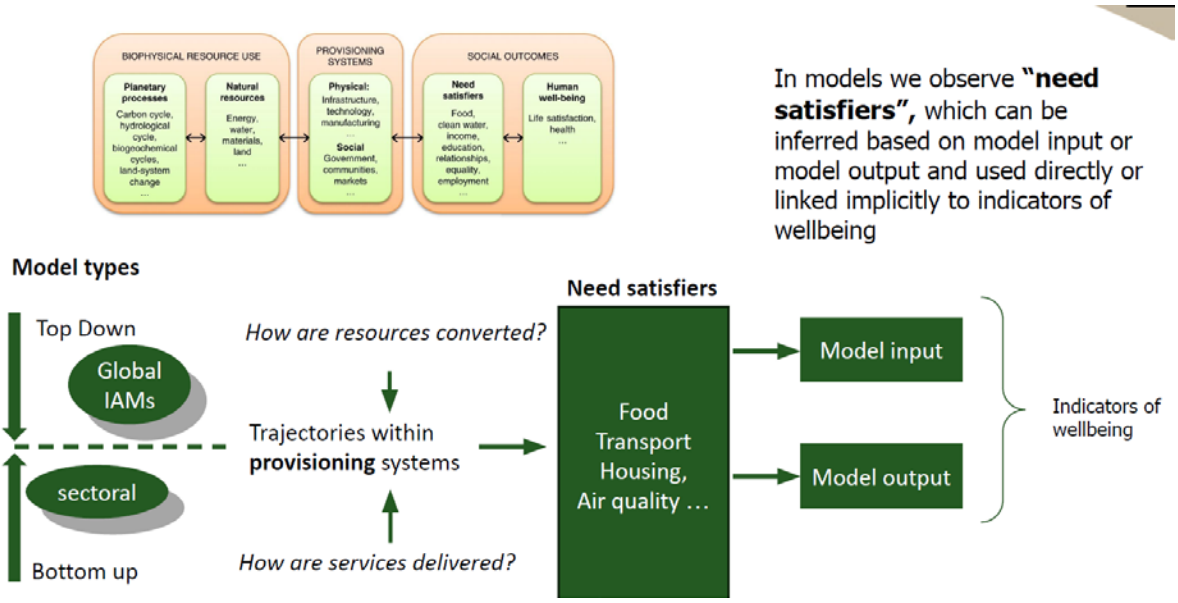


Figure 28. Proposed framework and conceptual set-up for EDITS.

Yamina Saheb, Openexp, France talked about ways of harnessing sufficiency. The definition of sufficiency by the IPCC is based on four pillars, with the goal of avoiding the demand for all natural resources while ensuring human well-being for everyone, regardless of their location, all within planetary boundaries. The EU's target relates to EU decisions but does not consider the contradiction to emission reductions in 1990, nor does it account for the EU's impact on the rest of the world. Decomposition analysis in the case of the EU reveals a missing carbon budget equivalent. Regarding the upper limit, the EU's final energy demand by 2050 should be below a certain threshold. Some approaches focus solely on emissions and do not consider the egalitarian impact of the carbon budget. The challenge is to achieve carbon neutrality without depleting the carbon budget of other countries.

Karthik Akkiraju, Yale School of the Environment, USA presented the subjective well-being cost of basic needs deprivation. He introduced fusionACS, which is a data science platform based on the American Community Survey. Indicators focus on whether consumption (expenditure) is correlated with subjective well-being / life satisfaction.

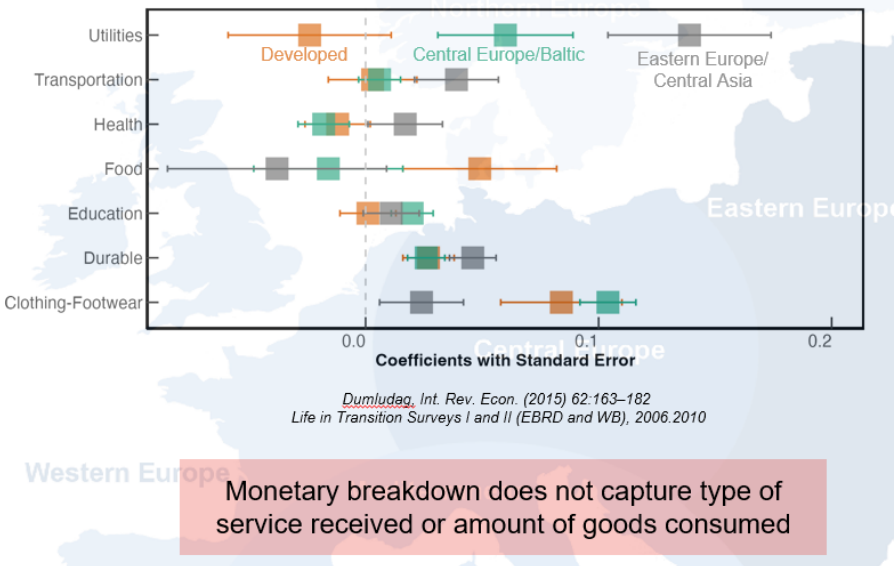


Figure 29. Life satisfaction related to spendings on different consumption categories/service. Sources: Dumludag, Int. Rev. Econ. (2015) 62:163–182 and Life in Transition Surveys I and II (EBRD and WB), 2006.2010

These presentations were followed by two break-out groups and then open discourse to discuss either the conceptual grounding and ways of assessing wellbeing or to describe and propose ways to develop an understanding of the provisioning systems. A few key points that were raised are:

- There are many terms used as alternates or substitutes for "wellbeing". For instance, literature in Europe doesn't often mention the SDGs directly.
- Wellbeing should be described using the concepts of needs and satisfiers. It was noted that the physical environment, culture, and institutions play a significant role in how people satisfy their needs.
- When understanding populations in the "sufficiency corridors", there are very large numbers of people between the minimum and maximum, and they are very heterogeneous; there is a connection to lifestyles work. One insight is that some groups in a population are very engaged in low-carbon transitions; others are not.
- Modeling regimes are locked in. They are set-up using GDP as a main driver and it is hard to move away from that.
- Policy-makers think along GPD and alike indicators and resetting these regimes is difficult. Yet a growth-centered approach punished the degrowth intentions, which is not appropriate.

Link to the recording is here.

Session 3. Complementary research and fast-track ideas

The session was dedicated to presentations by EDITS members to present their ideas, current research, and potential proposals for fast-track streams in EDITS. After an introduction by Benigna Boza-Kiss, IIASA, Austria, the speakers presented relevant demand-side research that are not part of, but closely related to EDITS. These were done in 3 break-out groups that participants were free to visit in a rotating manner. After the flash-talks, the discussion were opened into free discourse around the themes.

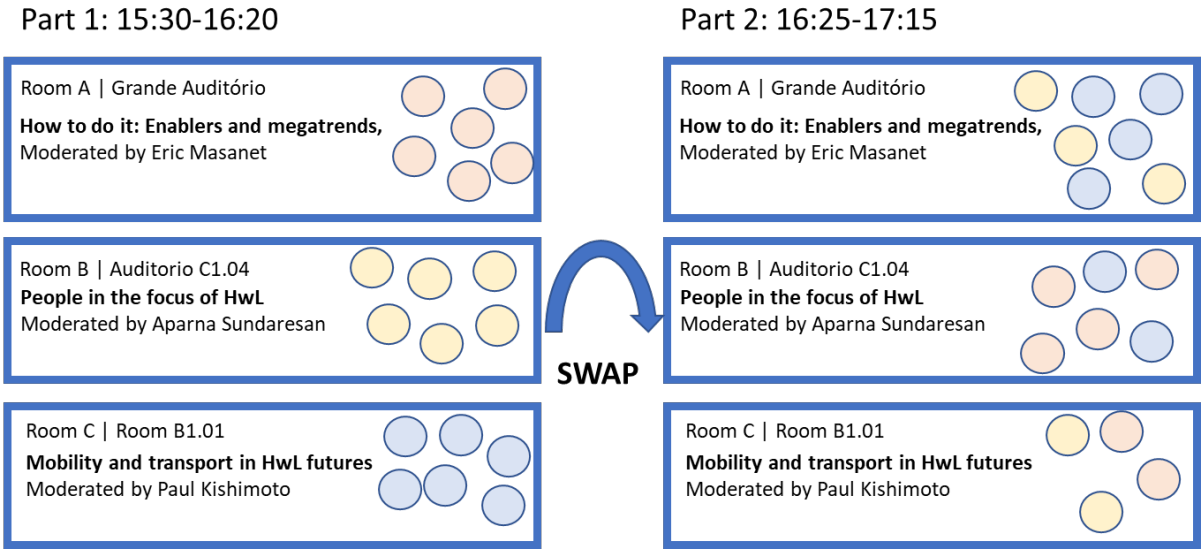


Figure 30. Session set-up

The flash presentations were:

How to do it: Enablers and megatrends

- Ayami Hayashi (RITE): How well could low energy demand society alleviate the mineral concerns on the pathways to decarbonization?
- Hiroyoshi Iwata (Tokyo University): Energy Innovation Finance in Japan and the Impact of Market and Policy Mechanisms
- Bianka Shoai-Tehrani (RTE): A proposal to elaborate national sufficiency scenarios
- Nuno Bento (Iscte): Digital convergence
- Charlie Wilson (University of Oxford): Digitalization

Mobility and transport in HwL futures

- Dominik Wiedenhofer (BOKU): Universal access to mobility infrastructure around the world with miminal GHG emissions
- Roberto Schaeffer (COPPE): The impact of road quality on diesel savings in the freight transport in Brazil
- Marlin Arnz (Technical University Berlin): What are decent mobility needs?
- Johannes Thema (Wuppertal Institute for Climate, Environment and Energy): Demand-side policy scenarios: the case of German passenger transport

People in the focus of HwL

- Jonathan Norman (University of Leeds): Public support and engagement for low energy futures
- Anne van Valkengoed (University of Groningen): How can we use theories and findings from psychology to more realistically model lifestyle changes?
- Vivien Fisch-Romito (University of Lausanne): Differentiating within the population the levers for reducing energy demand : the case of habitat in Switzerland
- Aparna Sundaresan (CSTEP): Balancing the Scales: Energy, Emissions, and Quality of Life in India

Link to the recording is here.

Session 4. Policy enablers and barriers to High with Low

The session was moderated by ***Arnulf Grübler***, International Institute for Applied Systems Analysis (IIASA), Austria. It dealt with policies and decisions that transform the setting in which energy services are provided and consumed. The policy framework significantly contributes to the effectiveness, costs and success of measures. The session provided a platform to critically evaluate existing and potential policies that interface with demand-side.

Greg Nemet, Wisconsin Energy Institute, USA talked about innovations for wellbeing, and highlighted that there are many opportunities to increase adoption of new technologies. He investigated the factors driving the speed of technological adoption in countries, and found that there is large dispersions in growth evidence, with strong evidence of growth acceleration, and spillovers have a dominant effect of spillovers.
Understanding technological growth – how fast different technologies are adopted and to what extent – can help us understand how newer technologies may grow. The growth trajectories that technologies have taken in the past differ; while some have grown quickly, others have grown slowly. Meeting the temperature goals of the Paris Agreement will require growth of technologies to reduce emissions, so understanding potential pathways for such growth is crucial. A newly published dataset includes time series data on technology adoption for over 200 technologies: https://cdr.apps.ece.iiasa.ac.at/story/hatch/

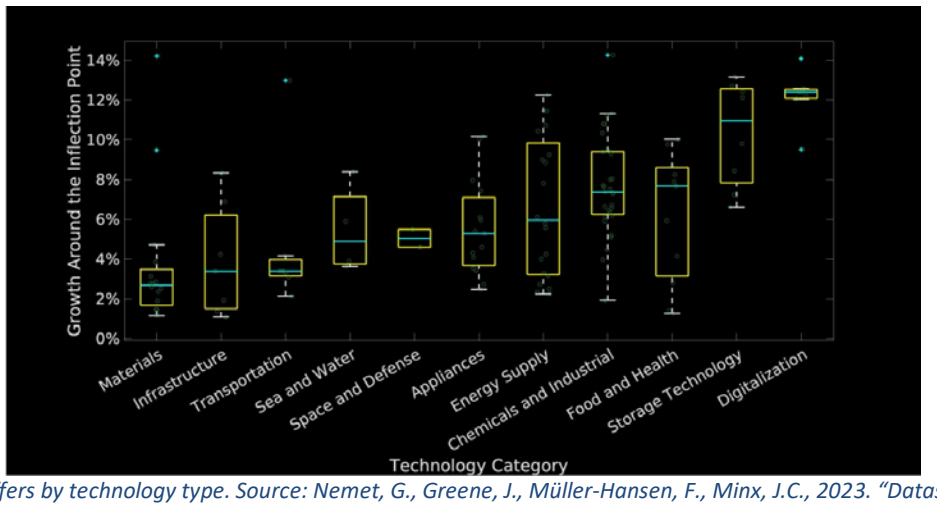


Figure 31. Adoption differs by technology type. Source: Nemet, G., Greene, J., Müller-Hansen, F., Minx, J.C., 2023. "Dataset on the adoption of historical technologies informs the scale-up of emerging carbon dioxide removal measures." Commun Earth Environ 4, 1–10. https://doi.org/10.1038/s43247-023-01056-1

Carina Zell-Ziegler, Oeko-Institut, Germany talked about how sufficiency policy can succeed – some thesis from current research. She reminded though that sufficiency not on individual behaviour change. Policy system improvement does not only mean adding new ones, but also abandoning or removing policies that are barriers to sufficiency (+behaviour). Examples include commuting tax allowance, flat rate taxation of privately used company cars, CBA methods in planning new roads. In housing: funding biased to new construction instead of refurbishment. An analysis of sufficiency policies in mobility show that economic instruments bare the least risks, fiscal instruments have the least barriers, while they need most input, and regulatory instruments feature the most supporting factors.

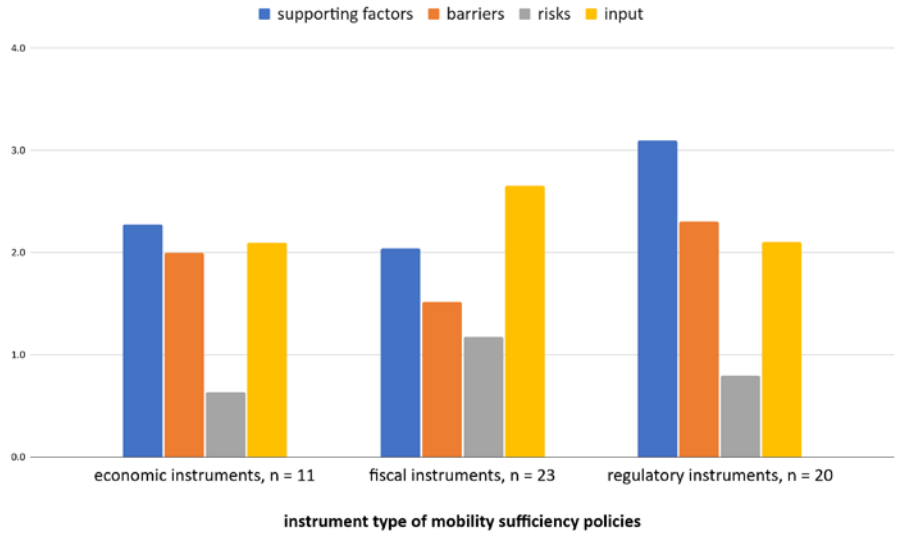


Figure 32. Policy mixes are essential. Research in progress by Carina Zell-Ziegler and Johannes Thema

Charlie Wilson, University of Oxford, the UK spoke about digitalisation as an enabler of HwL policies. In the HwL scenario narrative, digitalization is one of 3 main themes with innovation and decent living standards. Digitalization is a kind of general purpose technology with features such as trends, uptakes, acceptance that feature most technologies (see the presentation by Greg Nemet earlier). Four key governance themes were identified: (1) The importance of shared expectations, focusing on rapid peer effects and empowering end users. (2) Orienting incentives toward public purpose while avoiding digital divides and exclusions. (3) Coordinating access and use of shared infrastructure, advocating policy moves to open data commons and limit monopolistic behavior. (4) Digitalization can ensure that agency is distributed, it orients incentives towards public purpose, as well as coordinates access and use of shared infrastructure. For instance: open data commons, limit monopolistics behaviour.

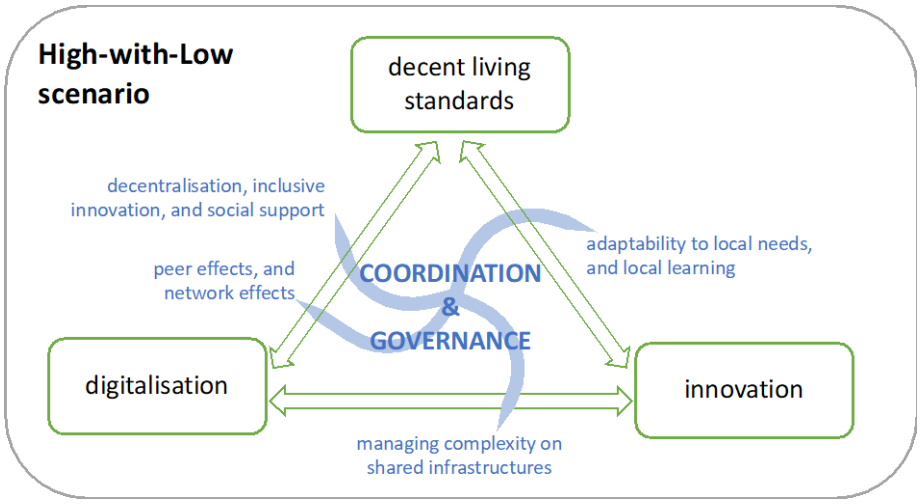


Figure 33. The main themes of the High with Low narrative. Source: https://pure.iiasa.ac.at/id/eprint/19036/1/WP-23-009.pdf

Gianfranco Gianfrate, EDHEC Business School was invited to give his reflections on EDITS and demand-side policies from a financial perspective. He highlighted that "finance" and "financial" rarely appear in EDITS, even though energy demand is highly a financial problem. Many assumptions are presented a about the responses to incentives, however these are overly optimistic about households' or firms financial literacy and ability to respond. In particular, he advised to consider the embedded financial aspects in policies. He pointed to the problematics of systemic consequences for the banking system, emphasizing its fragility. He mentioned the need to evaluate the impact of policies on the commercial element. He highlighted assumptions about governments having the financial capacity for transitions, emphasizing this concern for both developed and developing countries.

The following discussion covered a broad spectrum of points to consider and take up in EDITS related to policies and their ability to deliver change in sufficiency (demand reduction through excess removal), finance, and technology.

1) Rebound effects are highly controversial. Naturally, we want to avoid going back to high consumption through sufficiency policy rebounds, however rebound effects are valuable in the Global South to increase wellbeing.
2) There is a need to shift towards demand-side policies (efficiency, sufficiency). This brings about a qualitative change in household expenditures. Policy spillovers and borrowing can be very helpful, including for HwL technologies. Policy experimentation also an important way to avoid policies not happening fast enough.
3) Avoiding undesirable outcomes and doing it all is necessary for HwL, and it is not enough to cherry pick. In addition there is a priority issue: abandonment before replacement is preferred. Sufficiency is not heroic individual action, but systemic/societal action. Literature points to governance.
4) If we do not prioritize demand reduction, consequences are another threat of resource depletion. We have not managed yet to build enough renewable capacity to outpace demand growth, thus still building fossil fuel electricity generation.
5) Financing is a critical element. Even a scenario based on HwL needs significant capital, while challenging financing adaptation, and it assumes the ability to attract private capital through blended finance.
6) Digitalisation process seems to reinstate the current regime, which is not desirable for HwL. Technologies are nudging and shaping behaviour, usually without user consent and without energy and climate change intentions or goals. This motivates a focus on data sovereignty, and also on aligning such regulation with energy & climate change policy.
7) Digitalization ins intertwined with other technologies. The growth of e-bikes and the significance of demand-side investments, including electric vehicles, in the context of innovation and digitalization. On the other hand, digitalization has a role in substitution for physical mechanisms, and it has a potential to reduce electricity network investment requirements.
8) When assessing demand, we need to mindful of including all the pieces. E.g. in case of mobility, freight is not much talked / researched.

Link to the recording is here.

Session 5. Connecting research and policy

The session was moderated by ***Nebojsa Nakicenovic,*** International Institute for Applied Systems Analysis (IIASA), Austria. It was focused on the responsibilities and opportunities science has towards policy-making. It talked about the opportunities offered by demand-side policies, and discussed potentials and difficulties to implement these successfully. It explored what kind of research, data, indicators are necessary to inform these policies, and questioned why and why not the messages of urgency and ideas on solutions lead to related policies.

Diana Ürge-Vorsatz, Intergovernmental Panel on Climate Change (IPCC) & Central European University, Austria started the conversation by presenting what the IPCC can offer for delivering high wellbeing with low energy through policies. She started by drawing attention to the linkage between EDITS and IPCC, because EDITS is a community very essential to upcoming IPCC AR cycle. Appearance in AR6 WGIII was a success, because demand and services were well introduced and became the key pillar. First sentences in Summaries for Policy Makers mention efficiency and demand and communications materials also reflect this.

There are special reports coming up, where the EDITS community could have a critical place, e.g. Cities and climate change. To be more prominent, a recommendation is to connect to the big picture and add the recent climate context; this motivates a focus on climate-resilient development.

Nuno Bento, University Institute of Lisbon (Iscte), Portugal presented results from one of the fast-track streams within EDITS, and showcased "energy security from a demand-side angle". The research team found that "energy security" typically refers to security of supply, and therefore supply-side solutions are first considered. On the other hand, when considering energy security at the level of households, e.g. via indices such as Shannon (diversity) index, which is inversely correlated with energy intensity (= correlated with efficiency), the benefits are the opposite, and the value of demand-measures becomes evident. There is a consistent pattern of reducing intensity and improving diversity (~security), which was demonstrated via comparison of stylized policies in 14 countries. Interventions at the useful and final energy stage are more effective to improve energy security in countries. Focusing only on fossil fuel / import dependency gives a very different perspective: using only this indicator would motivate different interventions. The positive message is that sufficiency & efficiency can both improve security and reduce demand.

Jingjing Zhang, Lawrence Berkeley National Laboratory (LBNL), USA presented another EDITS fast-track activity, where about 10 teams from EDITS collaborate. This aims at bridging cost data and policy gaps to empower demand-side solutions. She connected her presentation with the earlier mentions of importance of financing. While the IPCC AR6 included information on many demand-side options, it was found that one reason for a heavy focus on the supply-side is better availability of cost information. At the same time, our data collection shows that demand-side efforts worldwide could avoid USD 100b needed for electric power system expansion. The fast-track aims at providing a transparent data library of cost and potential data on demand-side measures framed in a standardized framework for global context. By now, 213 references have been collected and arranged in the ASI framework, several sectors, and 10 regions. The results will be useful for policymakers, producers, individuals/households, and research communities.

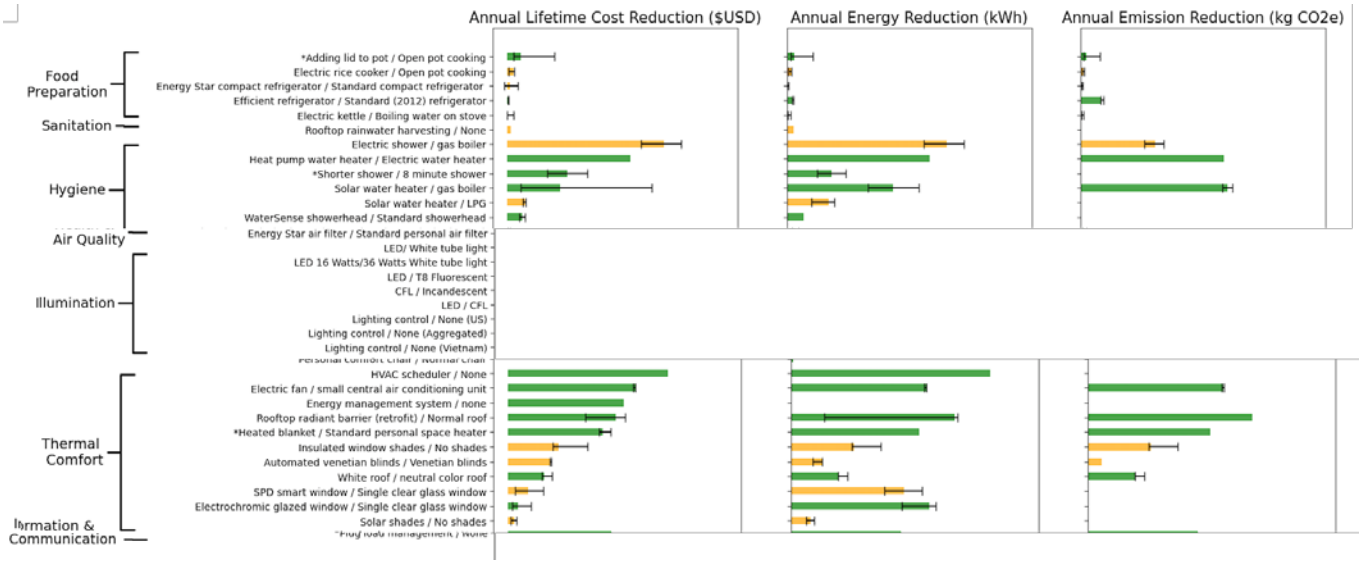


Figure 34. Initial results of costs of measures in the building sector. Source: own data.

Keigo Akimoto, Research Institute of Innovative Technology for the Earth (RITE), Japan gave a talk about demand-side emissions reduction and the related policies and measures. There is a large gap between bottom-up (IPCC Fig. SPM7) and top-down (IPCC Fig) emissions. Some factors influence the results, e.g. discount rates for investment. Higher rates are applied in end-use sectors or in developing countries, which skew their comparison to supply-side measures. Large amounts of emissions reduction potential with negative costs are estimated when typical discount rate, e.g., 5%/yr, are employed. There is a big difference in costs and potentials estimated by technology bottom-up studies and IAMs.

		Bottom-up studies (IPCC Fig. SPM7)	IAMs (IPCC Fig.3.33)
Below 20 USD/tCO_2eq	CO_2	($30.3\ GtCO_2/yr$)	**35～44 $GtCO_2/yr$**
	GHGs	**44.3 $GtCO_2eq/yr$**	($49～58\ GtCO_2eq/yr$)
Below 100 USD/tCO_2eq	CO_2	($15.5\ GtCO_2/yr$)	**23～34 $GtCO_2/yr$**
	GHGs	**29.5 $GtCO_2eq/yr$** [Reduction potential compared to baseline : 38 $GtCO_2eq/yr$ (32～44 $GtCO_2eq/yr$)]	($37～48\ GtCO_2eq/yr$)

Figure 35. Costs and potentials evaluation: 2030 global emissions. Sectoral bottom-up studies vs. IAMs. The numbers in parentheses for CO_2 and GHG emissions are the values taken from the report and simply converted to CO_2 or GHG using the actual values of the difference in global emissions in 2019 (14 $GtCO_2/yr$).

There are many factors that influence the actual discount rates: Technology-specific factors (e.g. High investment returns are required when the technology is not yet sufficiently mature); preferences of investors and consumers (e.g. Hidden costs), or factors related to the trading market, investment environment, and surrounding institutions (e.g. Under electricity liberalization, greater volatility in price indexes will demand greater returns on investments in power sources with large capital costs). While "implicit discount rates" explain high discount rates focusing mainly on bounded rational behaviors including heterogenous consumers, "user cost of capital" explain high discount rates focusing mainly on rational discount rates for using capitals or on rational rental prices of capital. In the estimation of the "user cost of capital", the bounded rational factors discussed in the "implicit discount rate" are considered to be included in the values of the respective parameters. In the end-use sectors, high discount rates for investment can be observed due to high depreciation rates, high expected price reductions, and other bounded rationality effects. Estimated by using DNE21+ model, and revised discount rates, the costs and potentials were reevaluated. The estimates by DNE21+ with standard discount rates are highly consistent with those by the IPCC IAMs. If discount rate of 5%/yr is adopted, the emissions reduction potentials increase, and fill some of the gaps to those by the bottom-up studies.

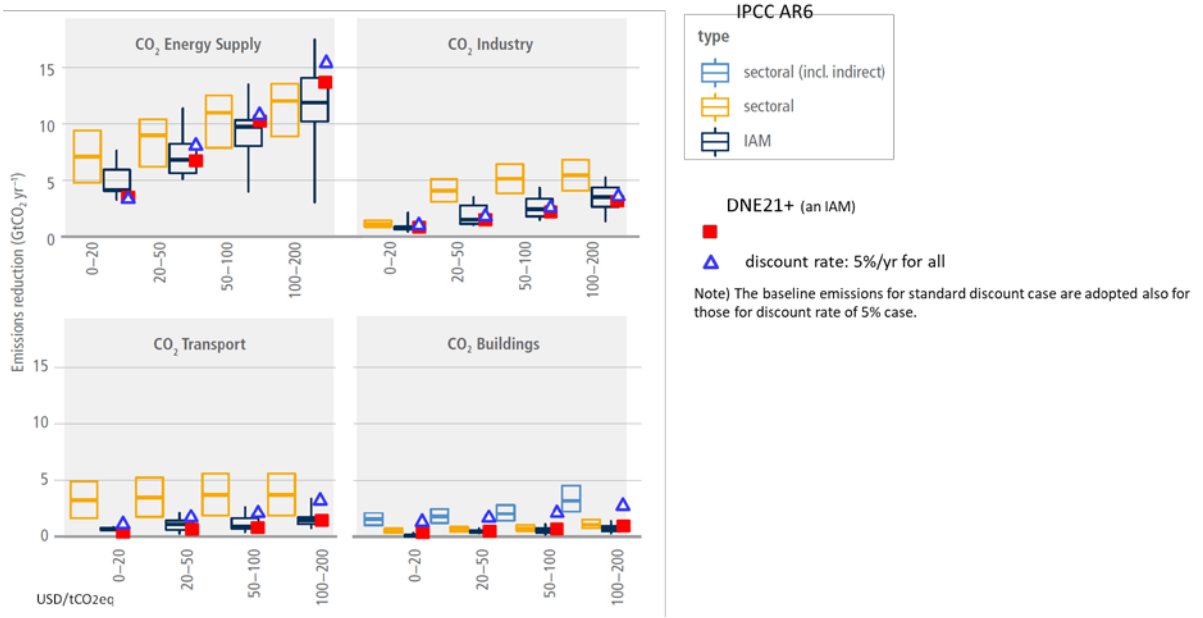


Figure 36. Global costs and potentials by sector and technology in 2030. Standard technology scenario & low discount rate of 5%/yr. Estimated by using DNE21+ model

The policy recommendations that come out of the research and modeling are:

- Relatively large hidden costs (large barriers of diffusions) are observed in end-use sectors in the real world, due to high depreciation rates, high expected price reductions, and bounded rationalities. Granular

technologies in end-use sectors can be expected to be higher cost reductions, but opposite direction effects also exist.

- Digitalization technologies could also contribute to reducing the hidden costs as well as inducing circular and sharing economies. In addition, changes to lifestyle preferences of long-term cycles for products with good qualities will be one of the potential opportunities for decreasing depreciation rates etc.
- Better evaluations of the reduction effects of the Scope 3 emissions, particularly of the down-stream, with policy supports, will be significant in order to make the incentive in firms. The Government of Japan is supporting the scheme of "avoided emissions."
- Measures providing electricity demand flexibilities, such as demand responses, which are also improved using digitalization technologies, are key for large shares of installation of VRE.
- Energy and climate policies tend to focus on energy supply sides more largely than on energy demand sides. Latter is broad policies and usually intervenes in other policies and other divisions within the government. Not small policy barriers exist. Anyway, in order to induce the demand-side policies, visualizations of end-use measures which contribute to high well-being with high research credibility will be important.

The following discussion reflected on the findings of the researches presented as well as on conclusions for EDITS close and longer-term plans.

1. Demand-side solutions and their costs have been shown for long, e.g. starting from Amory Lovins, 50 y ago said "negawatts instead of kilowatts."
2. There are controversies between what is said about the link of demand-side to wellbeing, while supply-side measures are not well connected to this discourse. For example, basic needs and satisfiers are better linked via demand-side measures, as they are direct or more immediate needs-satisfiers. As opposed to the supply side, which is further away in the chain of needs-provision. However, there is a continuum. Wellbeing is multidimensional and when focusing on the (merely) monetary cost, we omit most of the additional dimensions. When policymakers or readers ask for "costs", it is necessary to reflect all the dimensions, or educate them on (what we consider to be) the proper way to regard wellbeing.
3. There is a combination of factors that affect the way policy-makers and the public view demand-side solutions. The energy security fast-track makes a convincing case on effectiveness of HwL for energy security, while the study on implicit discount rates imply the reasons for considering these measures with high risk. There was a high agreement about the problematics of discount rates. This actually sets the scene for a case for government intervention: grants, informing people and supporting the provision of skilled labour.
4. There needs to be a strategy to play demand-side solutions more prominently in upcoming research communication, including the IPCC. IN case of IPCC, demand-side message to be included in all or many chapters. Besides the IPCC, another route is to communicate more directly with policymakers; which EDITS needs to embark on more directly.
5. "Urban solutions" are also "demand-side solutions" and EDITS could well conceptualize this. Could do this with a focus on buildings and transport sectors, also include effects of urban form. Construction sector, car production and road infrastructure, i.e. the upstream of "demand" could be another focus.
6. The words and expressions matter. It is hard to communicate an unambiguous meaning of the terms that are used in EDITS and we need effort to disentangle this. "What is demand? What are service provisioning systems?" harder to communicate/absorb. "High wellbeing" may be more accessible. Moving out of the mitigation community, it's important to find language that works beyond the bubble.
7. The way solutions are presented might also be a reason for difficulties in communicating about them. Though there is a need to find and talk about systemic solutions instead of individual technologies, however assessments still include a long lists of the latter

Link to the recording is here.

Session 6. Research presentations of the community

The session was held in Sintra, at Palácio Valenças. It examined how energy demand solutions and industrial policies interact for achieving multiple targets (such as economic, climate, wellbeing), and discussed options and challenges of implementation. The session was moderated by **Diana Ürge-Vorsatz**, Vice-Chair of the Intergovernmental Panel on Climate Change (IPCC).

After the welcoming words from the hosts and moderator, **Ricardo Paes Mamede, Dean of the School of Applied Digital Technologies, Iscte-Sintra, Portugal** talked about new trends in industrial policy and climate and sustainability goals. The session was actually disturbed by a political crises that just had broken out in Portugal that day previously. This was related to investments in green hydrogen and lithium extraction. It shows that there is (1) Increasing attention to political economy dimensions of green industrial policy. (2) Potential political conflicts between IP and climate/sustainability goals, esp. in international context. (3) Addressing challenges is necessary at national level and domestically. The size of a country matters for the political economy of green industrial policies. Smaller countries cannot rely on demand-side policy to control/influence technology development. While international competition could create diversity, it also means less rapid diffusion of new technologies. Aligning IP & sustainability requires careful international cooperation. Policies are targeted depending on decisions, and if there is new and growing consensus that demand-side solutions are beneficial, it will help governments to make decisions and set directions. Choosing adequate domestic policies means converging to the idea that industrial policy is more about not just simple incentives (subsidies) to adopt GHG-reducing measures, but should be tailored to national legitimate interests and specializations. Policy mixes are necessary (Kearns et al. 2019).

A viewpoint from the science and demand-side was provided by **Arnulf Grübler,** Distinguished Emeritus Research Scholar and founder of EDITS, International Institute for Applied Systems Analysis (IIASA), Austria, who presented the policy benefits of energy demand measures based on lessons learnt from EDITS. Demand side focus brings integrative policy framework for wellbeing & sustainable development. Demand measures relate to largest spillovers to jobs and to affordability. (plus also resilience and environment). Furthermore, they amplify impacts of specific supply-side policies. It is valuable to use a multidimensional indicator of wellbeing and energy security (12 components) that show large heterogeneity across countries linked to natural conditions, OECD or Global South, resource importer/exporter. Above these the findings are consistent across many countries: supply side options such as import substitution (biofuels for oil), change sources. Demand side solutions such electrification of transport, import buildings lead to larger improvements other than in actual diversity in fuels. Per affordability, supply-side policies lead to essentially no improvement. Demand reductions can lower energy bill to 1–2% of GDP, compared to 3–5% historically; lowers risk of exposure. There is a need to lower demand to allow renewable energy expansion to actually have an impact.

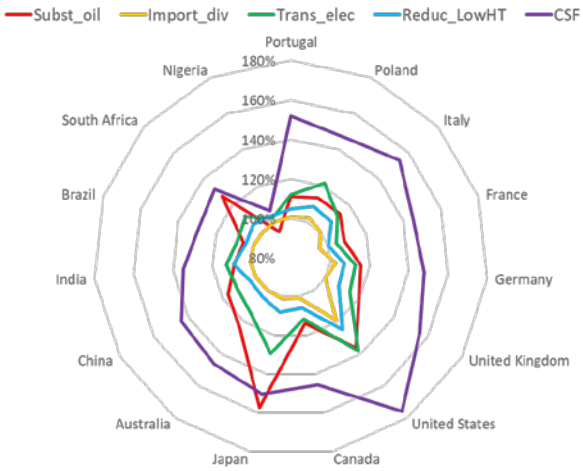


Figure 37. Impact of short-term Supply (red and yellow) vs. Demand- side (green and blue) Policies (10% of PE) vs. CSF (lila) Sufficiency Scenario on Multidimensional Security/Wellbeing. (12 indicators) Index for 15 Countries (2019 base = 100%). Source: Bento et al, Science

The next presentation was given by **Kenji Yamaji**, President of Research Institute of Innovative Technology for the Earth (RITE), Japan on policies in Japan towards low energy demand futures. He emphasized the need for a policy approach that combines both wellbeing and decarbonization. He gave an overview of the history of Japanese energy law from 1979 to 2022; now shifting to non-fossil energy. Previously energy saving was a topic in industry, only later were the buildings & transport sectors incorporated, then electricity load leveling added, finally extending policies to energy demand management. The central policy in Japan is the top runner regulation, which relates to energy-using equipment. Regulation is levied on their manufacturers. In 2022, shifting to non-fossil energy and optimizing demand for variable renewable energy were targeted, too. In parallel there are other initiatives, not necessarily directly linked to energy consumption. E.g. the 2016 "Society 5.0", the 2017 Connected Industries / Tokyo Initiative by METI, 2019 G20 lead to Karuizawa Innovation Action Plan for energy demand reduction by digitalization. This year (2023) there are discussions resulting from G7 JP on the principles for Circular Economy and Resource Efficiency.

The session hosted a panel and open discussion on strategies to improve global wellbeing and deliver climate targets.

1) The regime-internalized solutions are easier and more popular. It was shared that there are major plans in Portugal to install 10 GW of renewables in the sea. Is this a route for diversification? The innovative solutions do not easily build on the current structure of the economy. While we did not achieve all the targets, primary energy and secondary energy intensity decreased in Portugal (and globally), however less in terms of useful. Comparing nominal vs. real GDP, we see in the latter case the transition to services is less pronounced. Therefore, it is critical to define more ambitious and specific targets, including by increasing productivity in service sector?
2) Per messaging, when talking about solar PV, H_2, battery, this is concrete and simple. But for energy efficiency and sufficiency, there are hundreds of examples, and thus isn't this hard to digest?
3) It was discussed whether demand-side measures are actually more difficult in smaller countries. However it was counterargued that this is not the impact of demand-side policies on reduction of GHG emissions, but *as an industrial policy instrument*, for instance to trigger the emergency of new industries. For instance consider Japan vs. Portugal. Furthermore, Portugal is known to be among the success stories of renewables penetration in the EU; only one of 2 countries with >75% of electricity from RE in 2023-H1. According to local experts this success remains only an external beauty, but in order to achieve these outcomes, taxpayers paid a very high bill in FITs. At the same time, more energy independence has been achieved.
4) There are shifts (and wishful shifts) in developing countries towards more service economies, like it happened in the higher income countries. Yet, we need to remember that products will be still needed, and they need to be produced somewhere. There is an importance of structural change for rolling out demand-side solutions. The largest share of the economy is now the tertiary sector, which is not what was originally meant by "industry". "Industrial policy" can be called "development policy," social policy, etc. In HwL, most will come from recycling. Work will be distributed, including manufacturing. This will be genuine and transformative structural change.
5) The benefits in jobs of different types of policies is not well communicated. Interesting to see that demand-side job creation is greater, as well as the link to SDGs should be even more underlined. Job satisfaction elements include social usefulness; surveys reflect this. People may accept lower salaries for rewarding jobs.

Finally, **Nebojsa Nakicenovic**, Distinguished Emeritus Research Scholar at the International Institute for Applied Systems Analysis (IIASA), Austria gave his views, reflections and synthesis of what was discussed. His main message was that not having a policy is, in fact, also a policy. Coherence and consistence are important. Until today, demand opportunities are not taken up because not visible. It is widely agreed that businesses and policy-makers are much more rational than consumers, but this is often not the case.
Secondly, progress in research and understanding, not just directly but also knowing what the gaps are for the future. Sufficiency and efficiency are clearly good options, and missed opportunities will hurt soon. It needs to be synthesized, translated or somehow brought to a form that can be widely received and communicated.

Session 7. EDITS innovations to fill in research gaps

The session explored the space in-between sectors and was framed by a multiple of Working Groups: Sectors, Data, Complementary Protocol and Synthesis. It looked out of the box to pinpoint to key gaps in the conceptual framing and modeling of the sectors. This was followed by looking at the first results and lessons learnt from the complementary protocol, and discussing opportunities to represent wellbeing and other human benefits of demand-side better. The session was moderated by **Joyashree Roy**, Asian Institute of Technology (AIT), Thailand and India.

Part 1 was dedicated to gaps in demand sector modelling.

Alessio Mastrucci, International Institute for Applied Systems Analysis (IIASA), Austria summarized the key gaps in current practices of building sector representation based on the EDITS paper that was recently published. The team identified some best-practices in representation of low energy demand scenarios in buildings. The paper also explores cross-sectoral themes, and how they can be modeled. These included "Megatrends and DLS". Their dynamics are not yet well understood and thus hard to be integrated into models. Four key areas & related opportunities for further development were identified: (1) Spatio-temporal resolution and coverage. Especially Global South relative the Global North. Temporal: intra-daily. Useful sources would be remote sensing and meter data. (2) Granularity and heterogeneity, esp. distributional aspects. (3) Model dynamics: many things are simplified in representation. There is a need for endogenization, cross-model linkages. (4) Establishing cross-sectoral linkages. For instance urban system, link of urban form with mobility and building sectors.

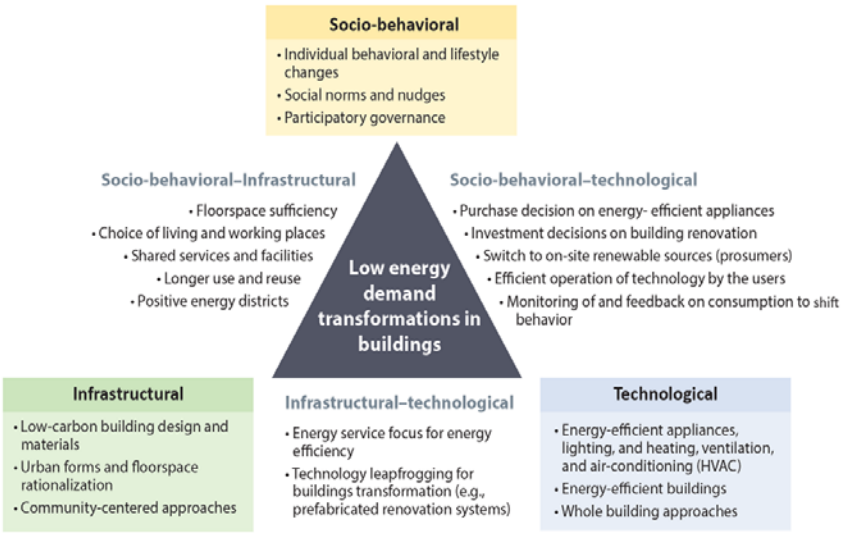


Figure 38. Analytical framework of building sector models. Source: Mastrucci, Niamir, Boza-Kiss, et al. Modeling Low Energy Demand Futures for Buildings: Current State and Research Needs. Annual Reviews of Environment and Resources (In press)

Luis Martinez, International Transport Forum (OECD-ITF), France gave an overview of key gaps in current practices of transport sector representation. The writing team is working towards complete draft of the literature review. The review is based on the assessment of and representation of phenomena & things endogenous to the transport sector. Key gaps 1: Connection between transport activity and land use management. Activity is an enabler for well-being, e.g. population density is only vaguely addressed by metrics of city size that affect trip length. To understand the implications of land-use mixture and 15-minute city on transport activity, mode choice, and derived externalities is currently not possible. Key gap 2: Connection of freight activity and the decarbonization of industry and energy-system-related flows. While freight is traditionally part of trade, mobility implications are understudied, while needed for a paradigm shift. Key gap 3: Rural transport (both passenger and freight) is still a significant and large share of activity/energy demand, especially in developing countries. Key gap 4: Frameworks, methods, phenomena, and policies are biased to the Global North, thus there is need for adjustment to the Global South. Key gap 5: Behavioural adaptation to constraints applied to "free choice" patterns of transport activity/consumption. Perception of social norms, gains/costs of transport activity and change. Key gap 6: Sophisticated demand

management policies, e.g. mobility credits & trading thereof should be brought into models, as well as they need to be studied more, e.g. digitalization.

Dominik Wiedenhofer, University of Natural Resources and Life Sciences (BOKU), Austria reviewed their conclusions about key gaps in current practices of industry sector representation based on the submitted paper. The paper reviews almost 100 studies in depth and has defined the development of modelling traditions connections.

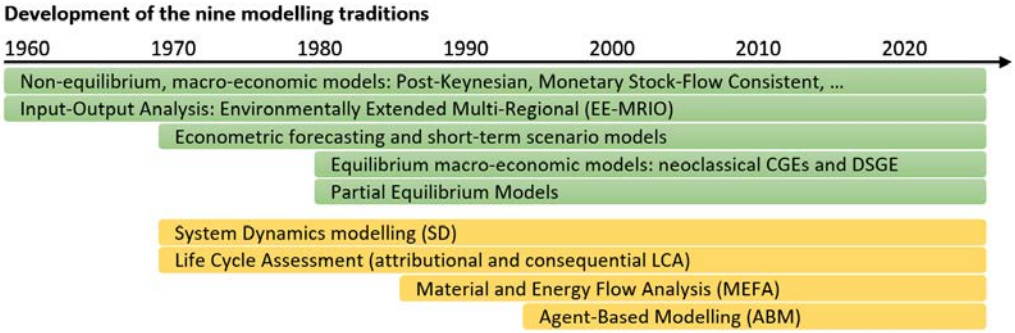


Figure 39. In-depth review of 77 innovative studies published in the last ~10 years. Source: upcoming paper Wiedenhofer et al. (submitted)

The team working on the paper concluded that low energy ad material demand (LEMD) assessment happens in all modeling traditions, but it's a niche. Remaining gaps are: (1) Materials cycles and stocks are not very well represented. (2) Differences in granularity and scope limit comparability and applicability. (3) Incoherence in system definitions and boundaries; lack of open data and documentation make it hard to do proper evidence synthesis. (4) Most innovative (conceptually exciting) studies are too aggregated to be very interesting. (5) Service provisioning measures are included in selective and disjoint manner. Leading to incomplete conclusions. Wellbeing is usually summed as GDP. (6) IPCC has one definition of "industry", other traditions have others. (7) Interdisciplinary perspectives are robust, interesting, and policy-relevant; but a flock. (8) SSPs are used a lot but don't have real information on service provisioning, and no proper LED or HwL variant.

Reactions were given by discussant, Leila Niamir, International Institute for Applied Systems Analysis (IIASA), Austria. She pointed out that key points repeated across 3 sectors: (1) Heterogeneity, variability, granularity; data on these. (2) Integration need and lack thereof, which could be improved for use of modeling. In line with this, EDITS also runs a fast-track stream on data mapping efforts. (3) There is complementarity of e.g. "agent-based" and "macro" models, and to combine them, we need new methods and data.
She concluded that EDITS a great place to take up these directions and opportunities. Finally, it is critical to move away from sectoral approaches, which stems from the IPCC perspective, that has always sectoral chapters. With the AR6, there was already progress because the demand chapter brought all these together.

There were further comments and additions received from the floor:

1. When per intersectionality is sought, we often end up going to IAMs and talk about soft-linking, but we often find applications lacking. This could be changed by improving demand models. Endogenizing and coupling are important but not always possible. Sometimes we can rely on linking and coupling instead of pushing endogenization too far. But this also can be difficult: data are structured differently.
2. There needs to be efforts to connect qualitative work to quantitative levels, which has proven difficult so far.
3. EDITS should connect with further communities including:
    a. system dynamics communities that are doing SDG assessments
    b. connect more to social sciences who actually work on what is service provisions, how is it acceptable, how does it contribute to wellbeing.
    c. Connection with urban level work
    d. the industry WG is planning to do online meeting series with a few exciting modeling teams. Post-Keynesians, ecological macro-econ, multi-sectoral models, DE environmental agency

4. In light of the title of the meeting and our overall aspirations, we started off by saying, how we can achieve a low demand future that meets 1.5°C. But we should move to high wellbeing future that is consistent with 1.5°C. First/intermediate step for this is to quantify wellbeing impacts of meeting DLS. Then we can say we have an idea of the aggregate effect of this. Second short-term pragmatic approach: how do we break down silos. We have tried IAMs and soft-linking; these are time-consuming activities and cannot have short-term impacts. We can do inter-linkage mapping (per DETRAS), and derive from this a priority to know which linkage matters most. Then try various research strategy to approach these.

Link to the recording is here.

Part 2 was dedicated to moving ahead with modelling.

Masahiro Sugiyama, University of Tokyo, Institute for Future Initiatives, Japan presented the Lessons from the first round of scenario collections and relevance of the SSP updates. EDITS is in the process of a "model complementarity project" (MCP). Submission status varies widely by models at the moment, but great progress has been made. Limitations are experienced because of data formats, conversion from model-native format, which make the process slow. We are moving ahead to include more models, more data. It has been seen that models don't endogenize some variables.

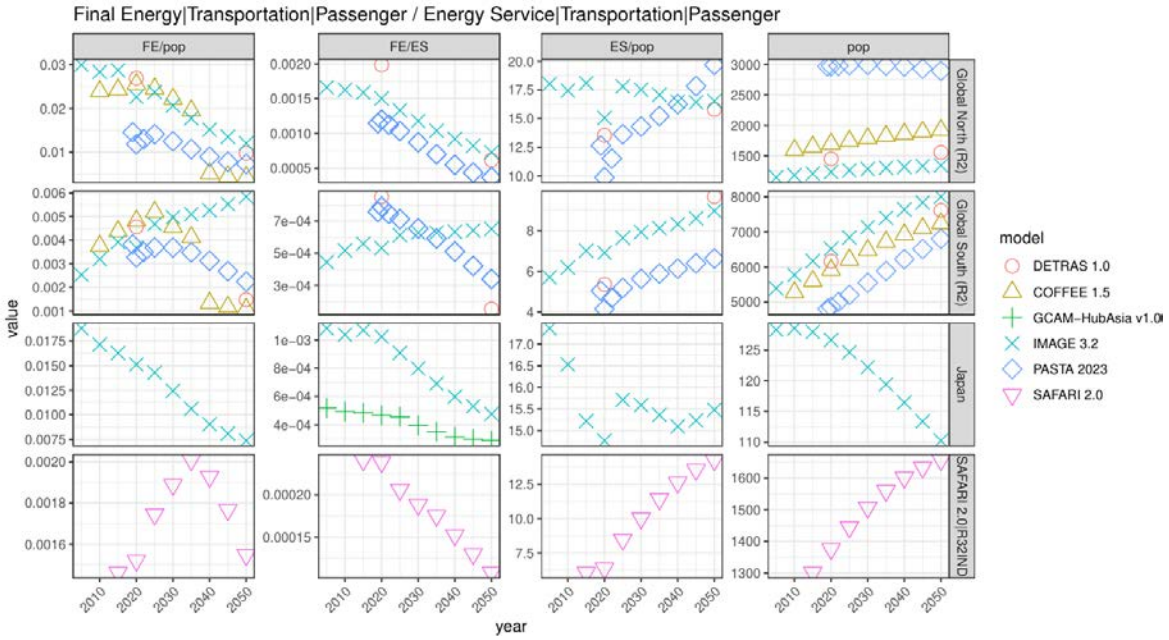


Figure 40. Kaya-like decomposition (passenger transport) for the submitted model data.

Reactions were given by discussant, **Nan Zhou**, Lawrence Berkeley National Laboratory (LBNL), USA. She was impressed with the results so far, acknolweding the enormous effort that has been going into this work. This is a very crucial outcome of EDITS that can empower more demand-resarch and analysis. There is a significant value in transparency per which storyline are being used by models. It is really hard to work with such comparison due to need for standardization, and establishing consistency of formats. It is puzzling why models have different results in some cases, and it will be exciting to disentangle the underlying reasons. In reference to EF China study, another model intercomparison: same definitions of storylines, often different results. Insights into the sources of these difference would be valuable for the modeling community.

Comments were received from the audience that restated the challenges across many other model exercises, indicating the data cleaning and standardization difficulties are "a universal problem", so not to be solved by EDITS alone, but by tapping into universal solutions: standards, shared tooling, etc. There could be an important role for IPCC in this, but also not solely theirs, either. Based on the experiences of one fast-track stream, the India DLS study

using 6 models, trying to do similar alignment. Diversity and ranges is a kind of insight, maybe we should not always try to flatten this in the service of "alignment". For instance, SAFARI has a different objective for their runs.

Link to the recording is here.

Session 8. Pathways for EDITS to improve wellbeing focus: Final comments, conclusions and way forward

It is important to take stock of the achievements, as well as identify the most effective intervention points, where EDITS could make largest impact on research and policy. The session offered an opportunity to highlight success from the past year, and express recommendations and preferences for steering the initiative in the coming period. The discussion was moderated by Benigna Boza-Kiss, IIASA, Austria.

A selection of comments and suggestions follow:

1. EDITS is moving towards being more action-oriented, things are moving forward. It is time that we communicate towards the outside about demand-side measures, invest in communications. There are key selling points: COP27 India launched a "life mission", changing lifestyles for environment; great overlap.
2. It is important that conceptual ideas to be linked to concrete modeling. Suggestion to consider realism of interpretations of scenario narratives in models, this helps to have acceptance with policymakers. In Japan and Korea sufficiency ideas are socially acceptable. There is a great improvement in understanding of sufficiency vs. last year's meeting.
3. This meeting has given a key insight on the interest from people in moving on from historical adoption of technologies, to instead historical adoption of behaviours. It would be interesting to show how attitudes and behaviours can change, including attitudes, behaviours, social innovation.
4. EDITS has become a relatively established community after a few years, and new interest finds us. The community is very Global North oriented and European; needs to be more representative to communicate widely.
5. In order to reach out and talk to the rest of the world, we need to be able to quantify wellbeing, connect with an economic community. HwL seems a solution to many problems facing the world—can we sell it under this heading. Along similar lines, we should be aware of being too academic-oriented; to be policy-relevant, need clear target to communicate, maybe need a vehicle to tell the story, a way to address the political-economic factors. More local case-studies are needed. In the policy communication realm, need a narrative framework that goes beyond "supply vs. demand". Equity within-countries is a main benefit/selling-point.
6. Regarding the meeting, face-to-face discussion was useful. Conceptual framework emerging for wellbeing. But others like sufficiency maybe not well-received outside this room. Examples in SF Bay area per zoning reform that are tied to sufficiency but framed in a different way. How do we identify these accessible & feasible actions? We have collected good insights from understanding of wellbeing, but still questions about how to define in different contexts and countries. How to connect with external stakeholders, esp. policymakers? There are other, competing issues, e.g. housing crises, energy access, etc.
7. The community calls for a working group on communication of narratives.
8. There is still a lot to do to connect outcomes to wellbeing indicators, which could be a focus. May want to go deeper in granularity and heterogeneity. Many outputs ready for communication; others not ready yet.

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ANNEX 2: EDITS ANNUAL CONFERENCE LIST OF PARTICIPANTS

The group:

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ANNEX 3: EDITS ANNUAL AGENDA AND PROGRAM

[all times in UTC, local time]

DAY 0 - November 6., Monday, 14:00-17:30

Focus of the day:

- Side-events, team working meetings
- EDITS members have access to the parallel Conference of *2023 Sus2Trans Project*
- Meet colleagues for a Cocktail if you are already around

12:30-14:30 Side-event by Costs and potentials fast-track Meeting room (B1.01)

Lead: ***Jingjing Zhang***, Lawrence Berkeley National Laboratory (LBNL), USA

Title: Cost of implementing demand-side solutions with high potential towards climate mitigation ambitions
Content: This will be a fast-track team meeting to improve/finalize the paper draft, i.e. a working/writing meeting
Who is expected: Only the fast track participants.
Preparations: Team members are requested to review draft paper outline, key messages, graphs, and data library.

14:30-16:00 Side-event by Crises as opportunities fast-track Clube (AA4.06)

Lead: ***Diana Ürge-Vorsatz***, Central European University (CEU), Austria

Title: Harnessing the power of crises through demand-side approaches
Content: First ideas will be presented, discussed and a working method agreed
Participants, who is expected: Fast-track members, and anybody who is interested to contribute to the fast-track work
Preparations: Not necessary

15:00-18:30 *Transformative Strategies for Sustainability Transitions* Auditório B2.03

Special invitation to a parallel event organized by Iscte. The *2023 Sus2Trans Project Closing Conference* presents the literature-derived decarbonization pathways and discusses case existing transformative business models, already aligned with some of these pathways. This event leads up to the EDITS conference. EDITS members are warmly invited. Find the detailed program in the attached document.

15:00-16:20 Opening and Session 1. Transformative strategies for climate mitigation and development

16:20-16:40 Coffee break Auditório B2.03

16:40-18:30 Session 2. Emerging transformations towards sustainability in practice and Closing

Closing ceremony of *Sus2Trans Conference* and **welcome cocktail for *EDITS***

18:30 – 19:00 Cocktail *Porto de Honra* Espaço de exposições

[all times in UTC, local time]

DAY 1 – November 7, Tuesday

Focus of the day:

- Understanding, describing and modelling wellbeing and its provisioning systems
- Presenting demand-related research outside of, but connected to EDITS
- Proposing new ideas for EDITS that can potentially lead to fast-tracks

9:00-09:30 Arrival and registration **Grande Auditório**

09:30-09:45 Welcome and introductions Grande Auditório

Nuno Bento, University Institute of Lisbon (Iscte), Portugal

Keigo Akimoto, Research Institute of Innovative Technology for the Earth (RITE), Japan

Bas van Ruijven, International Institute for Applied Systems Analysis (IIASA), Austria

09:45- 11:00 Session 1. Providing wellbeing for all Grande Auditório

Moderator: ***Bianka Shoai-Tehrani***, RTE, France

The session will highlight recent research within and in parallel to EDITS to discuss the conceptual grounding of the nexus of well-being and low energy and material demand futures. It will explore the human drivers of energy demand.

Just transition and wellbeing

Shonali Pachauri, International Institute for Applied Systems Analysis (IIASA), Austria

What is wellbeing in the Global South and how to achieve it

Joyashree Roy, Asian Institute of Technology (AIT), Thailand and India

Multidimensional welfare indices of the IPCC AR6 scenarios

Massimo Tavoni, CMCC and Politecnico di Milano, Italy

A systems perspective on sufficiency, wellbeing, and transition in the Swiss habitat

Sascha Nick, Laboratory of Environmental and Urban Economics (EPFL), Switzerland

Examining the impact of low carbon scenarios on perceived quality of life: pilot study in the Netherlands

Anne van Valkengoed, University of Groningen, the Netherlands

Panel discussion with the speakers and the audience

11:00-11:30 Coffee break Espaço de exposições

11:30-13:00 Session 2. Understanding wellbeing Grande Auditório

Moderator: ***Jubair Sieed***, Research Institute of Innovative Technology for the Earth (RITE), Japan

The session is framed by WG Wellbeing and WG Synthesis. Continuing the topics of the previous session, it will discuss wellbeing as the output of energy systems, while mitigating climate change and dependence on unproven/costly technologies. After a few introductory presentations, participants will break-out to discuss two related, but concrete topics: (1) conceptual review and assessing wellbeing, (2) provisioning systems for wellbeing.

How to think of wellbeing?

Sascha Nick, Laboratory of Environmental and Urban Economics (EPFL), Switzerland and ***Elina Brutschin***, International Institute for Applied Systems Analysis (IIASA), Austria [online]

Harnessing sufficiency

Yamina Saheb, Openexp, France

Subjective well-being cost of basic needs deprivation [online]

Karthik Akkiraju and Narasimha Rao, Yale School of the Environment, USA

12:00-13:00 Break-out groups

BOG 1: Conceptual review and assessing wellbeing
Grande Auditório

Discussion focus:

- What are the most relevant framing concepts that EDITS gravitates to?
- What methods (modelling and non-modelling) are most useful and should be engraved for EDITS activities?
- What are the steps to make wellbeing a central element of scenarios?
- What are the meanings of wellbeing depending on context: Global North/Global South; rural/urban, young/elderly, different genders, etc.? How can we represent heterogeneity in models?
- Should scenarios always have wellbeing focus and how can wellbeing be assessed? How to go beyond SSPs?
- Can we propose (quantitative) parameters that could be used by the models?

Lead by: ***Oreane Edelenbosch***, Universiteit Utrecht, the Netherlands and ***Massimo Tavoni,*** RFF-CMCC European Institute on Economics and the Environment (CMCC)

BOG 2: Provisioning systems of wellbeing
Auditorio C1.04

Discussion focus:

- How can we use low carbon solutions to provide wellbeing for all?
- What are the relevant technological, social and especially institutional and infrastructural requisites to provide wellbeing and wellbeing for all?
- How to ensure more inclusivity and justice?
- What is the role of sufficiency in both the Global North and the Global South? What are the resource implications?

Lead by: ***Linda Steg***, University of Groningen, the Netherlands and ***Roberto Schaeffer,*** Universidade Federal do Rio de Janeiro, Brazil

13:00-14:00 Lunch break Espaço de exposições

14:00-15:00 Session 2. cont. Understanding wellbeing Grande Auditório

Moderator: ***Roberto Schaeffer***, Universidade Federal do Rio de Janeiro, Brazil

The session from the morning is continued with reporting back to the plenary and identifying critical themes that demand-side research should be gravitating to in order to improve understanding and representing the human side of the energy-system and to identify the necessary elements and extents of the provisioning system.

14:00-14:15 **Reporting back** from the BOGs

Oreane Edelenbosch, Universiteit Utrecht, the Netherlands and ***Massimo Tavoni,*** RFF-CMCC European Institute on Economics and the Environment (CMCC), ***Linda Steg***, University of Groningen, the Netherlands

14:15-15:00 **Panel and open floor discussion** with:

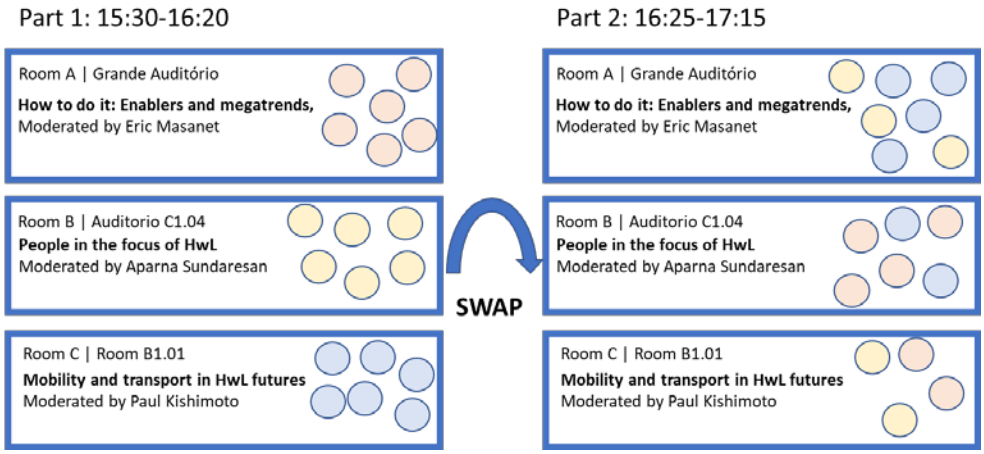
Souran Chatterjee, University of Plymouth, the UK
Charlie Wilson, University of Oxford, the UK
Kaveri Ashok, Center for Study of Science, Technology and Policy (CSTEP), India

15:00-15:30 **Coffee break** Espaço de exposições

15:30-17:15 **Session 3. Complementary research and fast-track ideas** Grande Auditório

The speakers will present relevant demand-side research that are not part of, but closely related to EDITS. After the flash-talks, the discussion will broaden up into free discourse around the themes.

The session will consist of two parts of 50 minutes each and take place in three parallel rooms each hosting 3-4 presenters. This will mean that each participant can visit two of the topics of their choice. See the schematic that explains the idea, where dots are the participants, who move from one break-out to another for the second part.



The flash presentations will be:

How to do it: Enablers and megatrends

- Ayami Hayashi (RITE): How well could low energy demand society alleviate the mineral concerns on the pathways to decarbonization?
- Hiroyoshi Iwata (Tokyo University): Energy Innovation Finance in Japan and the Impact of Market and Policy Mechanisms
- Bianka Shoai-Tehrani (RTE): A proposal to elaborate national sufficiency scenarios
- Nuno Bento (Iscte): Digital convergence

Mobility and transport in HwL futures

- Dominik Wiedenhofer (BOKU): Universal access to mobility infrastructure around the world with miminal GHG emissions
- Roberto Schaeffer (COPPE): The impact of road quality on diesel savings in the freight transport in Brazil
- Marlin Arnz (Technical University Berlin): What are decent mobility needs?
- Johannes Thema (Wuppertal Institute for Climate, Environment and Energy): Demand-side policy scenarios: the case of German passenger transport

People in the focus of HwL

- Jonathan Norman (University of Leeds): Public support and engagement for low energy futures
- Anne van Valkengoed (University of Groningen): How can we use theories and findings from psychology to more realistically model lifestyle changes?
- Vivien Fisch-Romito (University of Lausanne): Differentiating within the population the levers for reducing energy demand : the case of habitat in Switzerland
- Aparna Sundaresan (CSTEP): Balancing the Scales: Energy, Emissions, and Quality of Life in India

17:15-18:00 Side-event by HwL models review fast-track Grande Auditório

Lead: ***Masahiro Sugiyama,*** University of Tokyo, Institute for Future Initiatives, Japan

Title: High with low: harnessing the power of demand-side solutions for high wellbeing with low energy and material demand
Content: We will discuss the reviewer comments received and prepare the response, distribute review tasks
Participants, who is expected: Fast-track members only
Preparations: Check the reviewer comments and response:
https://1drv.ms/w/s!AjVwOJMltK8Kh75huGPwdTf8uCxtGg?e=eoqj3B

19:00-21:00 Social dinner in Lisbon

18:00 **Leaving** from Iscte by shuttle bus to the restaurant

19:00-21:30 **Dinner**

DAY 2 – November 8, Wednesday

Focus of the day:

- Policies and real life solutions for HwL

09:00- 10:30 Session 4. Policy enablers and barriers to High with Low Grande Auditório

Moderator: ***Arnulf Grübler***, International Institute for Applied Systems Analysis (IIASA), Austria

Policies and decisions transform the setting in which energy services are provided and consumed. The policy framework significantly contributes to the effectiveness, costs and success of measures. The session will provide a platform to critically evaluate existing and potential policies that interface with demand-side.

Innovations for wellbeing

Greg Nemet, Wisconsin Energy Institute, USA

How sufficiency policy can succeed – some thesis from current research

Carina Zell-Ziegler, Oeko-Institut, Germany

Policy for digitalisation as an enabler of HwL

Charlie Wilson, University of Oxford, the UK

Reflections from a finance perspective

Gianfranco Gianfrate, EDHEC Business School

Panel with speakers and open floor discussion

10:30-11:00 Coffee break Espaço de exposições

11:00-12:30 Session 5. Connecting research and policy Grande Auditório

Moderator: ***Nebojsa Nakicenovic***, International Institute for Applied Systems Analysis (IIASA),Austria

The session will be focused on the responsibilities and opportunities science has towards policy-making. It will capture the opportunities offered by demand-side policies, and discuss potentials and difficulties to implement these successfully. It will explore what kind of research, data, indicators are necessary to inform these policies.

What the IPCC can offer for delivering high wellbeing with low energy through policies

Diana Ürge-Vorsatz, Intergovernmental Panel on Climate Change (IPCC) & Central European University, Austria

Energy security from a demand-side angle

Nuno Bento, University Institute of Lisbon (Iscte), Portugal

Bridging cost data and policy gaps to empower demand-side solutions

Jingjing Zhang, Lawrence Berkeley National Laboratory (LBNL), USA

Demand-side emissions reduction and the related policies and measures

Keigo Akimoto, Research Institute of Innovative Technology for the Earth (RITE), Japan

Panel with speakers and open floor discussion

12:30-13:50 Lunch Espaço de exposições

14:00-18:00 Bus trip to Cabo da Roca and Sintra

18:00-19:30 Session 6. Policies for wellbeing and decarbonization Palácio Valenças

Moderator: ***Diana Ürge-Vorsatz***, Vice-Chair of the Intergovernmental Panel on Climate Change(IPCC)

The session will be held in Sintra, at Palácio Valenças. It will examine how energy demand solutions and industrial policies interact for achieving multiple targets (such as economic, climate, wellbeing), and discuss options and challenges of implementation.

18:00-18:10 **Welcome from Sintra and opening: New trends in industrial policy and climate and sustainability goals, *Bruno Parreira***, Vice-President of the City of Sintra

18:10-18:20 **A Portuguese strategy to recover the economy and deliver carbon neutrality, *Ricardo Paes Mamede***, Dean of the School of Applied Digital Technologies, Iscte-Sintra, Portugal

18:20-18:30 **Policy benefits of energy demand measures: lessons learnt from EDITS, *Arnulf Grübler***, Distinguished Emeritus Research Scholar and founder of EDITS, International Institute for Applied Systems Analysis (IIASA), Austria

18:30-18:40 **Policies in Japan towards low energy demand futures, *Kenji Yamaji***, President of Research Institute of Innovative Technology for the Earth (RITE), Japan

18:55-19:20 Panel and open discussion on strategies to improve global wellbeing and deliver climate targets

19:20-19:25 **Reflections and synthesis, *Nebojsa Nakicenovic***, Distinguished Emeritus Research Scholar at the International Institute for Applied Systems Analysis (IIASA)

19:25-19:30 **Closing words, *Ricardo Paes Mamede***, Dean of the School of Applied Digital Technologies, Iscte-Sintra, Portugal

20:00-22:00 Social dinner in Seteais

22:15 **Shuttle bus** from Seteais to Lisbon

DAY 3 – November 9, Thursday

Focus of the day:

- Cross-sectoral aspects
- Plans for EDITS

9:00-12:15 Session 7. EDITS innovations to fill in research gaps Grande Auditório

Moderator: ***Joyashree Roy***, Asian Institute of Technology (AIT), Thailand and India

The session will explore the space in-between sectors and framed by a multiple of Working Groups: Sectors, Data, Complementary Protocol and Synthesis. It builds on the calls from the community to move out of the box and advance knowledge in and around EDITS. We will build on the work already completed in the said Working Groups, to pinpoint key gaps in the conceptual framing and modeling these sectors. This will be followed by looking at the first results and lessons learnt from the complementary protocol, and discussing opportunities to represent wellbeing and other human benefits of demand-side better.

9:00-10:30 Part 1: Gaps in demand sector modelling

Key gaps in current practices of building sector representation

Alessio Mastrucci, International Institute for Applied Systems Analysis (IIASA), Austria

Key gaps in current practices of transport sector representation

Luis Martinez, International Transport Forum (OECD-ITF), France

Key gaps in current practices of industry sector representation

Leticia Magalar, CMCC European Institute on Economics and the Environment, Italy and ***Dominik Wiedenhofer***, University of Natural Resources and Life Sciences (BOKU), Austria

Reactions by discussant

Leila Niamir, International Institute for Applied Systems Analysis (IIASA), Austria

Open floor discussion

10:30-11:00 Coffee break Espaço de exposições

11:00-12:00 Part 2: Moving ahead with modelling

Lessons from the first round of scenario collections and relevance of the SSP updates

Masahiro Sugiyama, University of Tokyo, Institute for Future Initiatives, Japan and ***Bas van Ruijven***, International Institute for Applied Systems Analysis (IIASA), Austria

Reactions by discussant

Nan Zhou, Lawrence Berkeley National Laboratory (LBNL), USA

Open floor discussion

12:00-13:00 Session 8. Pathways for EDITS to improve wellbeing focus Grande Auditório

Moderator: ***Benigna Boza-Kiss***, International Institute for Applied Systems Analysis (IIASA), Austria

It is important to take stock of the achievements, as well as identify the most effective intervention points, where EDITS could make largest impact on research and policy. The focus will be on wellbeing and other human aspects of demand-side measures and solutions. We could identify expected outputs, such as impact, educational material, tools, etc.

Open floor discussion

13:00-13:15 Closing and Adjourn **Grande Auditório**

Bas van Ruijven, International Institute for Applied Systems Analysis (IIASA), Austria

Kenji Yamaji, President of Research Institute of Innovative Technology for the Earth (RITE), Japan

Nuno Bento, University Institute of Lisbon (Iscte), Portugal

13:20-14:30 Lunch
Clube (AA4.06)

14:30-16:00 Side-event by WG Transport Clube (AA4.06)

Lead: ***Luis Martinez***, International Transport Forum (ITF), France and ***Paul Kishimoto***, International Institute for Applied Systems Analysis (IIASA), Austria

16:00-17:30 Side-event by FT Data Gaps ***Clube (AA4.06)***

Lead: ***Leila Niamir***, International Institute for Applied Systems Analysis (IIASA), Austria and ***Oreane Edelenbosch***, Universiteit Utrecht, the Netherlands
Content: Working on the data and comparison
Who is expected: Fast-track members
Preparations: Finish coding

DAY PLUS 1 – November 10, Friday

9:00-12:00 Side-event by WG Wellbeing ***Clube (AA4.06)***

Lead: ***Linda Steg***, University of Groningen, the Netherlands and ***Sascha Nick***, Laboratory of Environmental and Urban Economics (EPFL), Switzerland

Title: Workshop on including wellbeing in models
Content: The meeting will start with 30 min introduction by organizers and participants, followed by 150 min (incl. breaks) working/writing. Key questions: share experiences of trying to include wellbeing into modeling; discuss which wellbeing approach would best fit which type of models and/or which type of questions (i.e., objective vs subjective wellbeing and individual vs societal wellbeing); decide what to focus on first in the WG wellbeing.
Expected output: (a) In-person connection between active WG Wellbeing people, (b) Outline of a common paper and/or plan for including wellbeing in different kinds of models
Who is expected: Everybody who is interested
Preparations: From the perspective of your work, what are the main insights and open questions related to including wellbeing in models? Fill in here

12:00-14:00 FT DLS India
Clube (AA4.06)

Lead: ***Souran Chatterjee***, University of Plymouth, the UK

Content: The meeting will have two parts
Part 1: Open for all EDITS members, and will consist of presenting the results of the work so far, plans and next steps.

Part 2: Closed meeting of the fast-track members to progress on writing and analysis

Review and compilation of best available data and modeling approaches for assessing the infrastructure energy use of data centers and artificial intelligence in energy demand models

Eric Masanet, University of California, Santa Barbara

February 29th, 2024

I. Introduction

Power utilization effectiveness (PUE) is arguably the most common energy performance metric reported by, and collected from, data center operators globally (Avelar et al. 2012). First introduced in 2007, PUE provided the data center industry with a straightforward metric to measure, communicate, and improve the energy efficiency of data center infrastructure equipment, which is broadly defined as including facility cooling, (de)humidification, uninterruptible power supply (UPS), power transformation, power distribution, and lighting equipment (Belady and Malone 2007; Brown et al. 2007).

While PUE has subsequently been critiqued as an imperfect, and even outdated, comparative measure of energy efficiency across data centers (Davis 2021; Masanet et al. 2013; Patterson et al. 2013), there is widespread recognition that its use has been responsible for large infrastructure energy efficiency improvements among data center operators historically. However, there is also evidence that such gains have stalled in recent years as many traditional data centers have already harvested low-hanging efficiency improvements and hyperscale data centers approach their practical PUE minima (Bizo 2023; Masanet et al. 2020).

Despite its imperfections as a comparative efficiency metric, PUE has been widely adopted by the data center energy analysis community for another purpose: estimating the total electricity use of data centers in bottom-up, macro-level energy systems models. Indeed, most bottom-up analyses published to date utilize PUE in a form following Equation 1, wherein the total electricity use of a fleet of data centers (which can be defined at different spatial scales and/or by market segments) is estimated by multiplying PUE by modeled data center information technology (IT) equipment electricity use (Mytton and Ashtine 2022). Data center IT equipment is generally defined as servers, storage devices, and

network equipment, which are typically located in data center IT racks and cabinets (Shehabi et al. 2016).

Average PUE values vary considerably by data center type, location, and efficiency practices, ranging from around 1.1 for the world's most efficient (typically hyperscale) data centers to greater than 2.0 for less efficient data centers (Lei and Masanet 2020). Therefore, the choice of PUE value can have a significant effect on estimated total data center electricity use in energy systems models.

(1) Total data center electricity use (Wh) = Total IT device electricity use (Wh) * PUE

The general form in Eq. 1 is also emerging as standard practice for estimating non-IT electricity use in emerging data center applications, particularly cryptocurrency mining and computing for artificial intelligence (AI). For example, Lei et al. (2021) have identified accounting for PUE as a best practice for blockchain energy modeling, whereas Patterson et al. (2022) have summarized a generalized approach for calculating the electricity use of training a machine learning (ML) model, which includes PUE (Eq. 2).

(2) Wh = (hours to train× number of processors × average power per processor) × PUE

As the global data center sector has expanded rapidly in recent years, there is a growing need for energy systems modelers to endogenize data center electricity use in climate mitigation scenarios. This advancement is necessary both to account for potential power load growth and to understand the net energy and emissions effects of digitalization (Bremer et al. 2023), as recommended in the IPCC's Sixth Assessment Report (Creutzig et al. 2022).

In particular, the rise of AI may have significant impacts on future electricity grids (deVries 2023), but it may also lead to significant systems-level energy and emissions effects, potentially positive or negative (Kaack et al. 2022). As such, a key driver for endogenizing data center electricity use is to understand the role of AI in climate change mitigation scenarios (Leurs et al, forthcoming).

To aid the energy analysis community in more confident and rigorous estimates of data center electricity demand moving forward—especially as relates to AI computing growth—this paper focuses on the following contributions:

1. What are the major sources of variability and uncertainty in reported PUE values that energy modelers should be aware of?
2. What is the current status of PUE reporting among data center operators?
3. In light of variabilities, uncertainties, and the state of PUE reporting, how might data center energy modelers account for PUE uncertainties?

II. Sources of variability and uncertainty in reported PUE values

This section identifies three major sources of variability and uncertainty that energy modelers should be aware of when selecting and applying PUE values in data center electricity use estimates: (1) measurement uncertainty; (2) climate variability; and (3) efficiency variability. Each of these factors will affect the confidence intervals associated with any reported PUE values used in modeling the future trajectories and data center and AI electricity use.

The discussions that follow refer to the following standard form of the PUE metric, as defined by the data center industry consortium the Green Grid (Avelar et al. 2012):

(3) PUE = [Total data center energy use]/[IT energy use]

Measurement uncertainty

Despite the simplicity of the PUE calculation in Eq. 3, there are variations in how both its numerator and denominator can be measured and reported by data center operators. These variations complicate the use of PUE as a comparative efficiency metric across data centers. Figure 1 presents a generic data center power chain schematic and summarizes the potential differences in measurement approaches. In practice, not all data centers will have all components of the depicted power chain; for example, some small data centers may not have backup power generators or uninterruptible power supply (UPS) equipment.

The Green Grid has established the measurement protocols summarized in Table 1 and encouraged data centers to indicate the corresponding "level" and measurement interval associated with PUE values that are publicly reported. The extent to which data center operators are complying with this guidance is discussed in Section III.

Table 1: PUE measurement reporting levels (Avelar et al. 2012)

	Level 1 (Basic)	Level 2 (Intermediate)	Level 3 (Advanced)
IT energy	UPS outputs (C)	PDU outputs (D)	IT equipment input (E)
Total facility energy	Utility inputs (A or A+B)		
Measurement interval	Monthly/weekly	Daily/hourly	Continuous

Note: letters in parentheses correspond to red circles in Figure 1

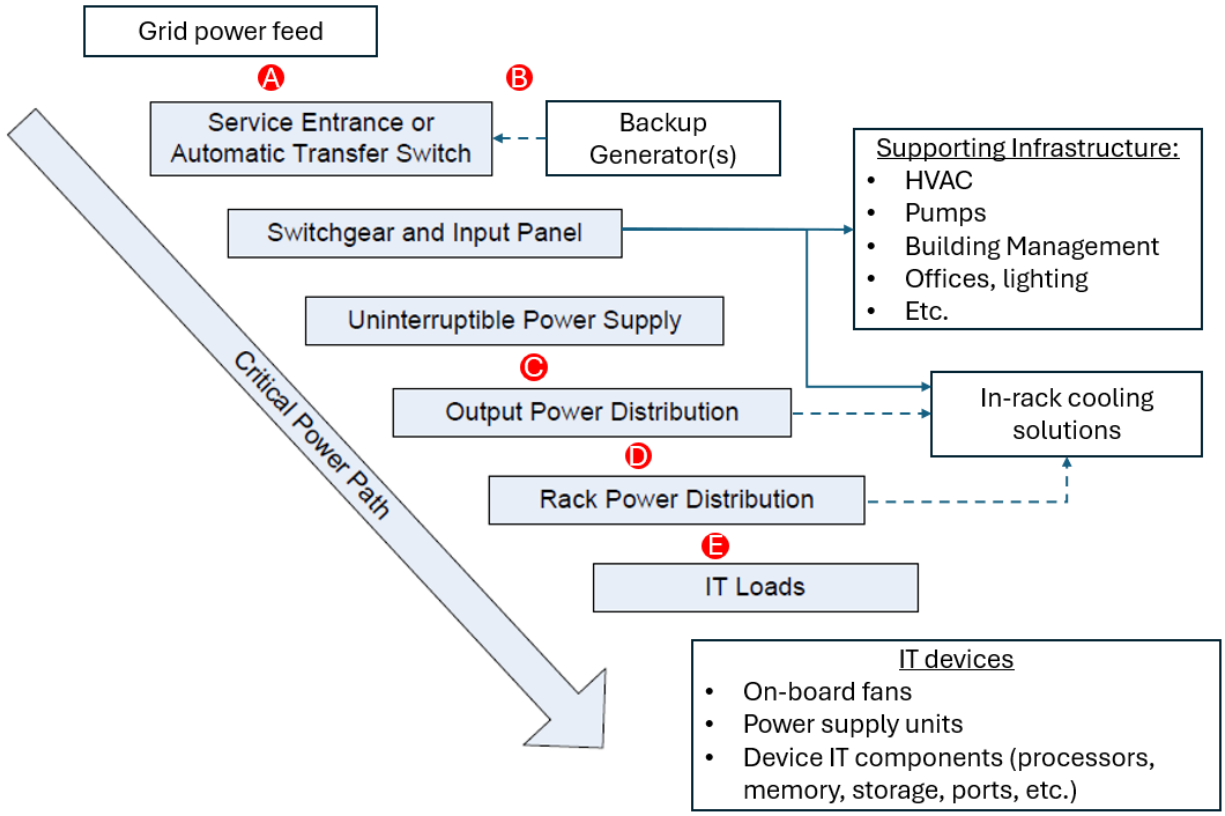


Figure 1: Schematic of data center critical power path and possible PUE measurement points (adapted from Avelar et al. 2012, Patterson et al. 2011, and Google 2024)

In bottom-up energy models, the analyst typically first estimates the electricity use of data center IT devices in a given region and/or market segment before using Eq. 1 to multiply by an assumed PUE value. Data center IT devices can include network switches, storage devices, conventional servers, and, increasingly, accelerated servers associated with AI computing or even cryptocurrency mining rigs. Most often, IT device electricity use is estimated on an annual basis (Mytton and Ashtine 2022), making annual average PUEs a common choice for use in Eq. 1.

The red circles in Fig. 1 indicate the different measurement points that energy modelers must be aware of to properly interpret a reported PUE value for use in Eq. 1. In the numerator, metered grid electricity values are generally available to data centers corresponding to Point A. However, for data centers that have backup power generators that cycle frequently, self-generation measured at Point B should also be included. Given that most data centers use backup power infrequently, the errors introduced to annual average PUE values when omitting backup power are expected to be small.

The primary uncertainties that are relevant to energy analysts are differences that exist between reporting levels, which correspond to denominator measurement Points C-E.

A Level 1 PUE is the most basic form, which includes all power path components downstream of the UPS outlet (Point C). In addition to IT device electricity use (Point E), Level 1 PUEs also include power losses associated with rack power distribution units (PDUs) and floor PDUs, and possibly even the electricity use of in-rack cooling solutions, such as rack-mounted fans, if they are connected to the floor PDU.

A Level 2 PUE includes all power path components downstream of the floor PDU outlet (Point D). In addition to IT device electricity use (Point E), Level 2 PUEs also include power losses associated with rack PDUs and possibly the electricity use of in-rack cooling solutions or even rack backup battery units (BBUs) if they are connected to the rack PDU.

A Level 3 PUE is considered the most advanced, and only includes measurements at the IT device plugs (Point E). However, depending on the configurations of the connected IT devices, Level 3 measurements may also include the electricity use of on-board fans, power supply units, and possibly even device-integrated BBUs, as shown in Figure 1.

Why are levels of PUE reporting relevant to energy modeling? Because it is important to ensure mathematical consistency when using Eq. 1 to arrive at a credible estimate of total data center electricity use. Most often, analysts develop bottom-up estimates of IT device electricity use on the basis of IT device stocks and average power draw assumptions (see, e.g., Shehabi et al. 2016; Schneider Electric 2021; Montevecchi et al. 2020).

If those IT stocks are consistent with Level 3 measurements, and a Level 3 PUE is applied, then there is mathematical consistency in Eq. 1. However, if IT stock electricity use is multiplied by a Level 1 PUE, which includes non-IT items in its denominator, the resulting value will underestimate total data center electricity use. Similarly, if IT stock electricity use that includes fan energy use is multiplied by a Level 3 PUE that excludes fans from its denominator, the resulting value will overestimate total data center electricity use.

If the PUE reporting level is known, analysts can reduce measurement uncertainty by ensuring mathematical consistency when employing Eq. 1. Suggestions for quantifying and communicating measurement uncertainty when PUE reporting levels are not known are offered in Section IV.

Climate variability

It has been well established that PUE values are correlated to outdoor climates, although the extent to which climate leads to PUE variability can also depend on a data center's deployed cooling type and its efficiency practices. For example, a data center in a hot dry climate can operate with low PUE values when deploying adiabatic cooling, efficient equipment, and high temperature set points, whereas a data center in a cool cry climate can operate with low PUE values by taking advantage of "free cooling" (Lei and Masanet 2021, 2022).

The extent to which climate variability will affect PUE uncertainty—and, hence, total data center electricity use uncertainty per Eq. 1—depends on the analyst's ability to choose a PUE value that matches the cooling system type(s) and location(s) of the data centers being analyzed. As shown in Figure 2, achievable PUE values vary by both cooling type and climate zone, as analyzed in Lei and Masanet (2022). Note, however, that Figure 2 also includes efficiency variability effects, which are discussed further in the next subsection.

In the best case, if the analyst can identify both the cooling system type and climate zone that applies to a given IT electricity use estimate, climate variability is minimized and only efficiency variability becomes relevant for uncertainty analysis. If the analyst knows the cooling system type, but the relevant geography spans multiple climate zones, Figure 2 can be used to quantify combined climate and efficiency uncertainty. For example, for a small direct-expansion cooled data center (Case 10), the practical range associated with the best climate zone (8 – subarctic) is 1.8-2.3, whereas the practical range associated with the worst climate zone (2B – hot-dry) is 2.0-2.6. Finally, if the IT electricity use estimate spans multiple cooling system types and climate zones, Figure 2 can be used to quantify uncertainties using variations in both cooling system types and climate zones, which will result in large uncertainties.

Efficiency variability

Efficiency variability relates to differences in installed equipment efficiencies, such as chiller coefficients of performance and fan efficiencies, and in operating factors, such as rack intake temperature setpoints. In Figure 2, efficiency variability is captured by the high and low PUE estimates for each cooling system type and climate zone from Lei and Masanet (2022). High and low PUE values capture poor and best-available efficiency practices, respectively. Efficiency variability can be accounted for in uncertainty estimates in the same manner as climate variability, given that the values in Figure 2 include combined climate and efficiency variable effects.

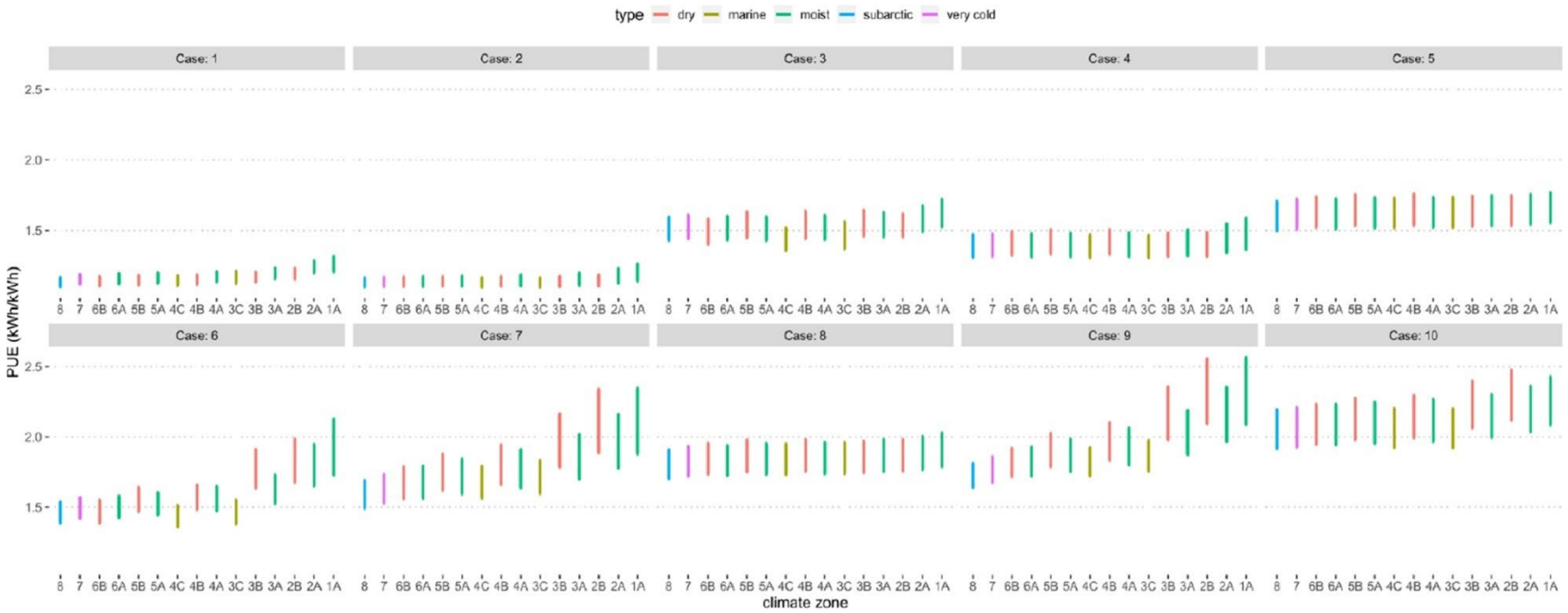


Figure 2: Annual average simulated PUE ranges (best to poor efficiency) by data center type and ASHRAE/IECC climate zone from Lei and Masanet (2022). Note: data center case descriptions are provided in Lei and Masanet (2022).

III. Availability and assessment of reported PUE data

To our knowledge, this study undertook the most comprehensive review and compilation of reported PUE data by specific (i.e., non-anonymized) data center operators. The goal was to provide a best-available reported PUE dataset for use by energy analysts, and in the context of the uncertainties discussed in the previous section. The review reflects historical reported PUE values as of late 2023, and included major data center operators in the hyperscale, cloud, colocation, and enterprise data center segments as summarized in Table A1. The PUE data that were compiled are summarized in Table A2 alongside relevant assessment data.

Table A1 reveals that, despite the widespread adoption of PUE by the data center industry, there are still many large data center operators that do not report PUE values publicly. Our search methods included reviewing company sustainability reports, websites, and financial filings. The non-reporting companies include a number of major companies that represent significant shares of the global hyperscale, cloud, and colocation market segments, including Apple, Amazon Web Services, ByteDance, Digital Realty, Tencent, and others. In fact, out of the roughly 150 companies that were reviewed, publicly-reported PUE data could only be found for less than one-third.

Table A2 contains all publicly-available PUE data that were found during our review, which contains roughly 400 reported PUE values. However, it is worth noting that two companies account for more than one-half of these values, given their detailed levels and long histories of reporting PUE data. Google has been reporting PUE data for its individual data centers since 2016, and for its overall fleet since 2008, which accounts for 130 values in our database. Oracle, which similarly reports PUE data for its individual data centers since 2020, accounts for around 90 values. In total, our review identified and compiled PUE data from 40 major data center operators.

Key characteristics of the reported PUE data, as relates to the sources of uncertainty discussed in Section II, are presented in Figure 3. Only one company (Google) among the forty identified describes the measurement approach associated with its reported PUE values, which is consistent with Level 3 reporting (Table 1). Only seven companies (Akamai, American Express, Google, Huawei, Navent, Oracle, and VMWare) report PUE values with sufficient geographical resolution to understand climate-related effects. None of the companies provided sufficient explanations of their cooling technologies and efficiency practices to understand efficiency-related effects.

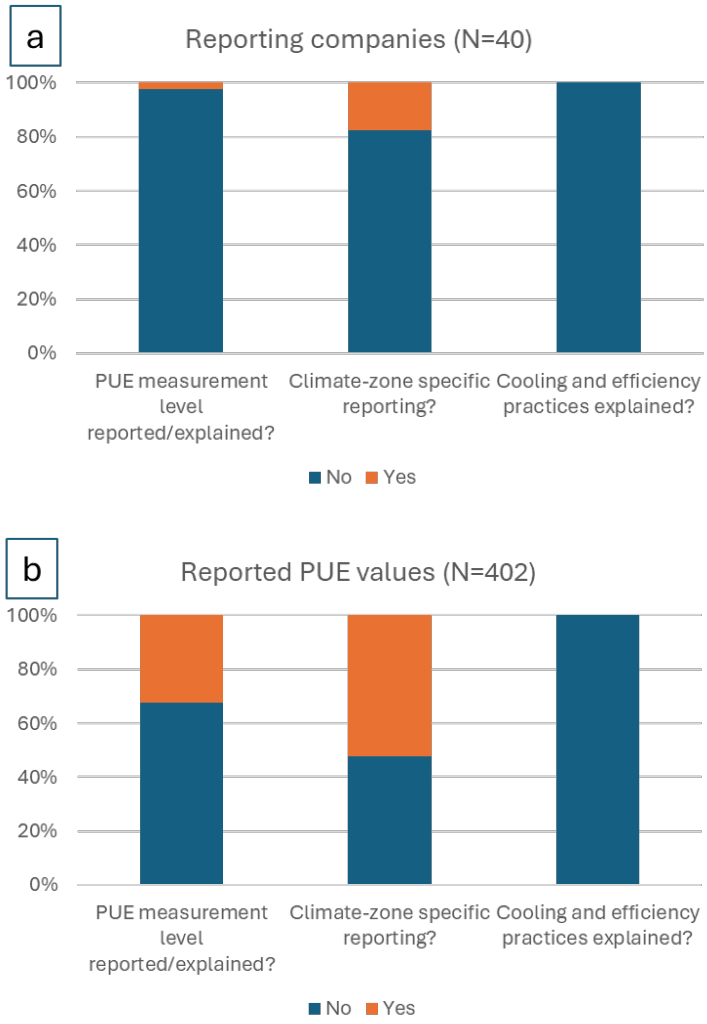


Figure 3: Summary of PUE value reporting characteristics by (a) company and (b) reported PUE value.

IV. Options for quantifying PUE uncertainties

While the reported PUE values in Table A2 begin to fill important empirical data gaps for use by data center energy analysts, they should not be used without proper understanding and treatment of uncertainties when applied in macro-level energy systems modeling contexts. Unfortunately, explicit treatment of parameter uncertainties has been rare in data center energy studies to date. As interest in modeling the data sector grows, explicit treatment of parameter uncertainty will provide more useful and rigorous scientific outputs while also promoting improved, and more widespread, reporting of PUE values by data center operators.

In the meantime, the following recommendations are made for better treatment of PUE uncertainties. These recommendations draw upon the discussions of uncertainties in Section II and the state of PUE reporting in Section III.

In the absence of any reported PUE data that are representative for modeled data center IT device stocks (i.e., its locations, cooling system types, and efficiency practices), analysts are encouraged to use the modeled PUE ranges summarized in Figure 2. Analysts should first identify the ranges of PUE values associated with all possible cooling system types and climate zones that could be associated with their modeled IT device stocks. From these identified ranges, analysts should then choose the lowest and highest values as the possible best and poor practice efficiency bounds, respectively.

For example, if a reasonable assumption for data center cooling technology is an air-cooled chiller without economizer (case 7), and the modeled region spans climate zones 3-6, a PUE range of 1.6 to 2.2 (see Figure 2) should be chosen to account for climate- and efficiency-related uncertainties. While this is a conservative approach, it errs on the side of caution when applying a PUE assumption in Eq. 1.

When reported PUE data are used, such as those summarized in Table A2, analysts should consider all sources of uncertainty discussed in Section 2. First, analysts must consider measurement uncertainties by ensuring that the denominator of the reported PUE value is mathematically consistent with how the analyst modeled the IT device stocks. Unfortunately, as discussed in Section III, only one company in Table A2 reported its measurement level alongside its PUE values.

Therefore, the analyst should ideally establish measurement uncertainty ranges when using the reported PUE value. First, the analyst should assume that the reported value represents a Level 1 measurement, given the motivation for companies to report the lowest PUEs possible. Second, the analyst should make assumptions about how the reported PUE value would change if the measurement point were moved from point C to point E in Figure 1.

For example, if a reported PUE value is 1.5, and typical floor PDU losses, rack PDU losses, and rack fans were assumed to amount to 15% of the IT load, the estimated Level 3 PUE would be 1.73. This is a conservative approach, but a sensible one due to lack of information provided by the reporting company. However, it requires the analyst to both make reasonable assumptions for loads that would be shifted from the PUE denominator to its numerator if measurements were made at point E instead of point C and to make those assumptions explicit in the analysis. Typical power use/loss values for PDUs, in-rack

cooling, and even server fans, power supply units, and backup batteries can be found in the literature, for example, in Ahmed et al. (2021) and Patterson et al. (2013).

Next, analysts should consider both climate and efficiency uncertainties. The analyst can use the measurement uncertainty adjusted range to identify possible cooling system types associated with the reporting company's possible climate zones, and from there identify best and poor efficiency practice bounds for all of the modeled IT device stock's possible climate zones as described above for the case when no reported PUE data are available. This procedure may also result in large uncertainty ranges. However, it also errs on the side of caution in light of lack of information provided by reporting companies and the possibility that the analyst will apply PUE values to climate zones beyond those in which the reporting company operates.

Considerations for liquid cooling and artificial intelligence

Historically, most data centers have operated with average power densities below 20 kilowatts (kW) per rack and air cooling of IT devices (Uptime Institute 2023). However, with the rise of AI computing may come much higher rack power densities, necessitating a shift to liquid cooling for adequate heat removal. Liquid cooling can take various forms, including water- or dielectric-cooled cold plates, one- or two-phased full immersion systems, or partial immersion systems.

When it comes to modeling liquid-cooled IT equipment moving forward, particularly for AI computing devices, there are several important considerations when using a PUE-based approach in a form similar to Eq. 1. First, the modeled ranges in Figure 2 only apply to different common air-cooled systems operating in different climate zones; these ranges should not be used for liquid-cooled systems. Second, given the historical predominance of air-cooled systems and the lack of clarity on which cooling system types are included in the reported PUE values in Table A2 (see Fig. 3B), it is not likely that these reported values include significant fractions of liquid cooling.

Third, and importantly, if (or when) liquid cooling systems are increasingly deployed in the future, it is likely that liquid cooling may only be applied to the high power-density racks in a data center and not to all racks. Due to their costs, complexities, and perceived risks (e.g., coolant leaks), liquid cooling is not likely to be deployed in lower power-density racks, which may contain conventional servers, storage devices, and/or network switches and for which traditional air-cooled technologies perform well. According to an Uptime Intelligence (2023) survey (n=183), over two-thirds of respondents expected to use liquid cooling in fewer than 20% of their IT racks in the next 3-5 years.

This means that analysts must consider overall facility PUEs that take both systems into account in their numerators and denominators or use partial PUE methods to assign the energy use of different cooling systems to different IT device electricity loads. A method for utilizing partial PUEs is presented in Avelar et al. (2012). However, early data suggest that there are interaction effects to consider, wherein the use of liquid-cooling can enable greater operational efficiencies in air cooling through higher chilled water and supply air set points (Heydari et al. 2022). Therefore, the use of total facility (rather than partial) PUEs may be preferable.

Finally, empirical data on liquid-cooling systems and hybrid liquid- and air-cooled data centers are still emerging in the literature. For initial assumptions, readers are referred to Heydari et al. (2022).

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VI. Acknowledgements

EM gratefully acknowledges the support of Lillian Liu, who reviewed, compiled, and checked many of the PUE data contained in Table A2.

VII. Appendix

Table A1: Summary of companies reviewed (as of late 2023)

Company Name	Is PUE reported via ESG/sustainability reports, websites, and/or financial filings?
@Tokyo	No
21Vianet	Yes
365 Data Centers	No
Accenture	No
Activision	No
Adam	No
Adobe	No
ADP	Yes
AIMS	No
Airtrunk	Yes

Akamai	Yes
Alibaba	Yes
Aligned Energy	Yes
Amazon/AWS	No
American Express	Yes
Apple	No
Armor (FireHost)	No
AT&T	No
AtHub	No
Bai	No
Baidu	Yes
Baosight Software	No
Box	No
British Telecom	No
BT Global Services	No
ByteDance	No
CA Technologies	No
Capital One	No
Carbonite	No
CDN77	No
CDNetworks	No
CenturyLink	No
China Mobile	Yes
China Net Center	No
China Telecom	Yes
China Unicom	No
ChinaCache	No
Chindata Group	Yes
Cirrascale	No
Cisco	No
Citrix	No
Cloud HQ	No
Cloudera	No
Cloudflare	No
Cogent	No
Cologix	Yes
Colt Data Center Services	No
Compass	No
CoreSite	Yes
Coromatic	No
CSF Group	No

CTC (ITOCHU Techno-Solutions)	No
CyrusOne	Yes
Cyxtera	No
Data Foundry	No
Databank	Yes
Datapipe	No
DCI Holdings	No
DCI Technology Holdings	No
Deep Cognition	No
Dell	No
Deutsche Telekom	Yes
Digiplex	Yes
Digital Ocean	No
Digital Realty	No
DocuSign	No
Domino	No
Dr. Peng Group	No
Dropbox	Yes
eBay	No
EdgeConneX	Yes
EdgeCore	No
Electronic Arts	No
Equinix	Yes
Evoque Data Center Solutions	No
Exoscale	No
Fastly	No
FIS	No
Floyd Hub	No
Fujitsu	Yes
GDS	Yes
Global Switch	No
Google	Yes
GPU Eater	No
HP	No
HPE	No
Huawei	Yes
IBM	Yes
Intel	No
Internap	No
Interxion	No
Intility	Yes

Intuit	No
Iron Mountain	No
IronGate	No
iSeek	No
JD	Yes
JPMorgan	No
KDDI Group	No
Lambda	No
Leader GPU	No
LinkedIn	No
Lumen	No
Macquarie	No
Mastercard	Yes
Medidata	No
Meta (Facebook)	Yes
Microsoft	Yes
Naver	Yes
Netflix	No
Neutrality	No
Next DC	Yes
NIMBIX	No
NTT Group	Yes
NVIDIA	No
On Ramp	No
One Wilshire	No
Oracle	Yes
PayPal	No
Penguin Computing	No
QTS	Yes
R Systems	No
Rackspace	No
Rescale	No
Sabey	No
Salesforce	Yes
SAP	Yes
Sentinel	No
ServiceNow	No
ServiceStream	No
Sinnet	No
Soutscale	No
Spark	No

Splunk	Yes
Stream	No
SUNeVision	No
Switch	Yes
Symantec	No
T5 Data Centers	No
Telehouse	No
Telstra	No
Tencent	No
Teraco Data Environments	No
Tierpoint	No
Twitter	No
Vantage	No
Verizon	No
Verne Global	No
VISA	Yes
VMware	Yes
Vocus	No
Wangsu	No
Web Werks	No
Workday	No
Yahoo	No
YourDC	No
Zendesk	No
Z-Holding/Yahoo	Yes

Table A2: Summary of compiled PUE data

Company	Applicable year	Facility scope	Geographical scope	Temporal scope	PUE	PUE measurement level	Link to Original Report
21Vianet	2022	Fleet-wide PUE	Mainland China	Annual Average PUE	1.37	Not Specified	https://www.vnet.com/upload/portal/PDF/2022esgreporten.pdf
21Vianet	2021	Fleet-wide PUE	Mainland China	Annual Average PUE	1.37	Not Specified	https://www.vnet.com/upload/portal/20220420/70a36cd710e66b1a76767411c4c927ac.pdf
ADP	2021	Fleet-wide PUE	Global	Annual Average PUE	1.69	Not Specified	https://sustainability.adp.com/pdf/ADP-2021-Corporate-Responsibility-Report.pdf
ADP	2020	Fleet-wide PUE	Global	Annual Average PUE	1.65	Not Specified	https://sustainability.adp.com/pdf/ADP-2021-Corporate-Responsibility-Report.pdf
Airtrunk	2022	Fleet-wide PUE	Asia-Pacific	Annual Average PUE	1.32	Not Specified	https://airtrunk.com/wp-content/uploads/2023/10/AirTrunk-FY23-Sustainability-Report-FINAL-Online.pdf
Airtrunk	2021	Fleet-wide PUE	Asia-Pacific	Annual Average PUE	1.35	Not Specified	https://airtrunk.com/wp-content/uploads/2023/01/airtrunk-sustainability-report-2022-online.pdf
Akamai	2022	Fleet-wide PUE	Global	Annual average PUE	1.4	Not Specified	https://www.akamai.com/resources/research-paper/akamai-2022-environmental-social-governance-report
Akamai	2021	Fleet-wide PUE	Global	Annual average PUE	1.25	Not Specified	https://www.akamai.com/resources/research-paper/akamai-sustainability-report-2021
Akamai	2021	Single location PUE	Virginia, US	Annual average PUE	1.19	Not Specified	https://www.akamai.com/resources/research-paper/akamai-sustainability-report-2021
Akamai	2021	Single location PUE	New Jersey, US	Annual average PUE	1.25	Not Specified	https://www.akamai.com/resources/research-paper/akamai-sustainability-report-2021
Akamai	2020	Fleet-wide PUE	Global	Annual average PUE	1.4	Not Specified	https://www.akamai.com/content/dam/site/en/documents/sustainability/sam-csa-2021.pdf
Akamai	2020	Single location PUE	New Jersey, US	Annual average PUE	1.15	Not Specified	https://www.akamai.com/content/dam/site/en/documents/sustainability/sam-csa-2021.pdf
Akamai	2020	Single location PUE	Virginia, US	Annual average PUE	1.2	Not Specified	https://www.akamai.com/content/dam/site/en/documents/sustainability/sam-csa-2021.pdf
Akamai	2019	Fleet-wide PUE	Global	Annual average PUE	1.4	Not Specified	https://www.akamai.com/content/dam/site/en/documents/sustainability/sam-csa-2020.pdf
Akamai	2019	Single location PUE	New Jersey, US	Annual average PUE	1.09	Not Specified	https://www.akamai.com/content/dam/site/en/documents/sustainability/sam-csa-2020.pdf
Akamai	2019	Single location PUE	Virginia, US	Annual average PUE	1.15	Not Specified	https://www.akamai.com/content/dam/site/en/documents/sustainability/sam-csa-2020.pdf

Akamai	2018	Fleet-wide PUE	Global	Annual average PUE	1.4	Not Specified	https://www.akamai.com/content/dam/site/en/documents/sustainability/sam-csa-2020.pdf
Akamai	2017	Fleet-wide PUE	Global	Annual average PUE	1.45	Not Specified	https://www.akamai.com/content/dam/site/en/documents/sustainability/sam-csa-2020.pdf
Akamai	2016	Fleet-wide PUE	Global	Annual average PUE	1.5	Not Specified	https://www.akamai.com/content/dam/site/en/documents/sustainability/sam-csa-2020.pdf
Alibaba	2022	Fleet-wide PUE	Global	Annual average PUE	1.247	Not Specified	https://data.alibabagroup.com/ecms-files/1452422558/5feb0e46-f04b-4d9c-9568-e4a5912db37e.pdf
Alibaba	2021	Fleet-wide PUE	Global	Trailing twelve-month (TTM) PUE	1.3	Not Specified	https://doc.irasia.com/listco/hk/alibabagroup/annual/2021/ar2021.pdf
American Express	2022	Single location PUE	Phoenix, AZ	Annual Average PUE	1.57	Not Specified	https://www.americanexpress.com/content/dam/amex/en-us/newsroom/pdfs/AXP_2022-2023_ESG_Report.pdf
American Express	2022	Single location PUE	Greensboro, NC	Annual Average PUE	1.48	Not Specified	https://www.americanexpress.com/content/dam/amex/en-us/newsroom/pdfs/AXP_2022-2023_ESG_Report.pdf
American Express	2021	Single location PUE	Phoenix, AZ	Annual Average PUE	1.59	Not Specified	https://s29.q4cdn.com/330828691/files/doc_downloads/esg_resources/2022/AXP-2021-2022-ESG-Report.pdf
American Express	2021	Single location PUE	Greensboro, NC	Annual Average PUE	1.72	Not Specified	https://s29.q4cdn.com/330828691/files/doc_downloads/esg_resources/2022/AXP-2021-2022-ESG-Report.pdf
American Express	2020	Single location PUE	Phoenix, AZ	Annual Average PUE	1.61	Not Specified	https://s29.q4cdn.com/330828691/files/doc_downloads/esg_resources/AXP-2020-2021-ESG-Report.pdf
American Express	2020	Single location PUE	Greensboro, NC	Annual Average PUE	1.57	Not Specified	https://s29.q4cdn.com/330828691/files/doc_downloads/esg_resources/AXP-2020-2021-ESG-Report.pdf
Baidu	2022	Fleet-wide PUE	Global	Annual average PUE	1.16	Not Specified	https://esg.baidu.com/resource/1ee27a97-5b29-6c2b-a2c5-afc521543f70/Baidu_2022_ESG_Report.pdf
Baidu	2021	Fleet-wide PUE	Global	Annual average PUE	1.16	Not Specified	https://esg.baidu.com/resource/1ecd4d7e-c148-6e91-8dd5-556f11239ccc/Baidu%202021%20Environmental,%20Social%20and%20Governance%20Report.pdf
Baidu	2020	Fleet-wide PUE	Shanghai, Shenzen, and the US	Annual average PUE	1.14	Not Specified	https://esg.baidu.com/en/article/Baidu_2020_Environmental,_Social_and_Governance_Report
Baidu	2019	Fleet-wide PUE	Shanghai, Shenzen, and the US	Annual average PUE	1.14	Not Specified	https://esg.baidu.com/en/article/Baidu_2019_Environmental,_Social_Governance_Report
Baidu	2018	Fleet-wide PUE	Shanghai, Shenzen, and the US	Annual average PUE	1.16	Not Specified	https://esg.baidu.com/en/article/Baidu_2019_Environmental,_Social_Governance_Report
China Mobile	2021	Fleet-wide PUE	Mainland China	Annual Average PUE	1.3	Not Specified	https://www.chinamobileltd.com/en/ir/reports/ar2021/sd2021.pdf

China Mobile	2022	Fleet-wide PUE	Mainland China	Annual Average PUE	1.3	Not Specified	https://www.chinamobileltd.com/en/ir/reports/ar2022/sd2022.pdf
China Telecom	2021	Fleet-wide PUE	Mainland China	Annual Average PUE	1.3	Not Specified	https://www.chinatelecom-h.com/en/ir/presentations/annpre220317.pdf
China Telecom	2022	Fleet-wide PUE	Mainland China	Annual Average PUE	1.25	Not Specified	https://www.chinatelecom-h.com/en/ir/presentations/annpre230322.pdf
ChinDataGroup	2023	Fleet-wide PUE	China	Annual average PUE	1.21	Not Specified	https://www.chindatagroup.com/about/sustainability.html
CoreSite	2021	Fleet-wide PUE	United States	Annual average PUE	1.39	Not Specified	https://assets.website-files.com/5d95bce2cfbd82ab2ca712a8/62bc62b96dae29593abecca6_CoreSite%20Sustainability%20Report.pdf
CoreSite	2020	Fleet-wide PUE	United States	Annual average PUE	1.42	Not Specified	https://assets-global.website-files.com/5d95bce2cfbd82fc0aa712b1/60bda5c5d2ea404627606d9c_60ba3c82df0e49ab6cbc46cd_CoreSite%20CSR%202020_FIN.pdf
CoreSite	2019	Fleet-wide PUE	United States	Annual average PUE	1.4	Not Specified	https://assets-global.website-files.com/5d95bce2cfbd82fc0aa712b1/60bda5c5d2ea404627606d9c_60ba3c82df0e49ab6cbc46cd_CoreSite%20CSR%202020_FIN.pdf
CoreSite	2018	Fleet-wide PUE	United States	Annual average PUE	1.47	Not Specified	
CyrusOne	2022	Fleet-wide PUE	Global	Annual average PUE	1.45	Not Specified	https://documents.cyrusone.com/wp-content/uploads/2023/05/2023-Sustainability-Report-Final-CyrusOne.pdf
CyrusOne	2021	Fleet-wide PUE	Global	Annual average PUE	1.48	Not Specified	https://cyrusone.com/wp-content/uploads/2022/07/CyrusOne-2022-SustainabilityReport.pdf
CyrusOne	2020	Fleet-wide PUE	Global	Annual average PUE	1.51	Not Specified	https://cyrusone.com/app/uploads/2021/11/2021-Sustainabilty-Report_Final.pdf
CyrusOne	2019	Fleet-wide PUE	Global	Annual average PUE	1.5	Not Specified	https://cyrusone.com/app/uploads/2021/11/2021-Sustainabilty-Report_Final.pdf
CyrusOne	2018	Fleet-wide PUE	Global	Annual average PUE	1.54	Not Specified	https://cyrusone.com/app/uploads/2021/11/2021-Sustainabilty-Report_Final.pdf
Databank	2021	Fleet-wide PUE	Global	Annual Average PUE	1.72	Not Specified	https://www.databank.com/wp-content/uploads/2022/05/FINAL-2021-ESG-Report.pdf
Databank	2020	Fleet-wide PUE	Global	Annual Average PUE	1.7	Not Specified	https://www.databank.com/wp-content/uploads/2022/05/FINAL-2021-ESG-Report.pdf
Databank	2022	Fleet-wide PUE	United States, Europe	Trailing twelve-month (TTM) PUE	1.56	Not Specified	https://databank.drift.click/271713ab-4e35-4c99-93dd-312d36cc51e5
Deutsche Telekom	2022	Fleet-wide PUE	Germany	Annual average PUE	1.5	Not Specified	https://www.cr-report.telekom.com/2022/management-facts/strategy/cr-strategy-management#atn-19487-19493,atn-19487-19492,atn-19487-19491

Deutsche Telekom	2021	Fleet-wide PUE	Germany	Annual average PUE	1.49	Not Specified	https://www.cr-report.telekom.com/2022/management-facts/strategy/cr-strategy-management#atn-19487-19493,atn-19487-19492,atn-19487-19491
Deutsche Telekom	2020	Fleet-wide PUE	Germany	Annual average PUE	1.5	Not Specified	https://www.cr-report.telekom.com/2022/management-facts/strategy/cr-strategy-management#atn-19487-19493,atn-19487-19492,atn-19487-19491
Deutsche Telekom	2019	Fleet-wide PUE	Germany	Annual average PUE	1.56	Not Specified	https://www.cr-report.telekom.com/2022/management-facts/strategy/cr-strategy-management#atn-19487-19493,atn-19487-19492,atn-19487-19491
DigiPlex	2020	Fleet-wide PUE	Oslo, Stockholm, Copenhagen	Annual Average PUE	1.48	Not Specified	https://mb.cision.com/Public/7526/3435359/8ffecba6beaefaf4.pdf
Dropbox	2022	Fleet-wide PUE	United States	Annual Average PUE	1.2	Not Specified	https://aem.dropbox.com/cms/content/dam/dropbox/warp/en-us/esg/Dropbox-2022-Impact-Fact-Sheet-published.pdf
Dropbox	2021	Fleet-wide PUE	United States	Annual Average PUE	1.2	Not Specified	https://aem.dropbox.com/cms/content/dam/dropbox/warp/en-us/esg/2021_ESG_Impact_Report.pdf
Dropbox	2020	Fleet-wide PUE	United States	Annual Average PUE	1.32	Not Specified	https://aem.dropbox.com/cms/content/dam/dropbox/warp/en-us/esg/2021_ESG_Impact_Report.pdf
Dropbox	2019	Fleet-wide PUE	United States	Annual Average PUE	1.27	Not Specified	https://aem.dropbox.com/cms/content/dam/dropbox/warp/en-us/esg/2021_ESG_Impact_Report.pdf
EdgeConneX	2021	Fleet-wide PUE	Global	Annual Average PUE	1.27	Not Specified	https://www.edgeconnex.com/wp-content/uploads/2022/08/2021-EdgeConneX-Sustainability-Report-Final.pdf
EdgeConneX	2020	Fleet-wide PUE	Global	Annual Average PUE	1.26	Not Specified	https://www.edgeconnex.com/wp-content/uploads/2022/08/2021-EdgeConneX-Sustainability-Report-Final.pdf
EdgeConneX	2019	Fleet-wide PUE	Global	Annual Average PUE	1.27	Not Specified	https://www.edgeconnex.com/wp-content/uploads/2022/08/2021-EdgeConneX-Sustainability-Report-Final.pdf
Fujitsu	2022	Fleet-wide PUE	Japan	Annual Average PUE	1.57	Not Specified	https://www.fujitsu.com/global/documents/about/resources/reports/sustainabilityreport/2023-report/fujitsudatabook2023e.pdf
Fujitsu	2021	Fleet-wide PUE	Japan	Annual Average PUE	1.56	Not Specified	https://www.fujitsu.com/global/about/resources/reports/sustainabilityreport/2022-report/
GDS	2020	Fleet-wide PUE	Mainland China	Annual Average PUE	1.34	Not Specified	https://www.gds-services.com/esg2021/docs/GDS-ESG-Report-2020.pdf
GDS	2021	Fleet-wide PUE	Mainland China	Annual Average PUE	1.32	Not Specified	https://www.gds-services.com/esg2021/docs/GDS-2021-ESG-Report.pdf
Google	2022	Fleet-wide PUE	Global	Q42022 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Douglas County, Georgia	Q42022 Trailing twelve-	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/

				month (TTM) PUE			
Google	2022	Single location PUE	Lenoir, North Carolina	Q42022 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Berkeley County, South Carolina	Q42022 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Montgomery County, Tennessee	Q42022 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Jackson County, Alabama	Q42022 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Loudoun County, Virginia	Q42022 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Loudoun County, Virginia (2nd facility)	Q42022 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	New Albany, Ohio	Q42022 Trailing twelve-month (TTM) PUE	1.14	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Council Bluffs, Iowa	Q42022 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Council Bluffs, Iowa (2nd facility)	Q42022 Trailing twelve-month (TTM) PUE	1.08	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Papillion, Nebraska	Q42022 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/

Google	2022	Single location PUE	Mayes County, Oklahoma	Q42022 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Midlothian, Texas	Q42022 Trailing twelve-month (TTM) PUE	1.16	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	The Dalles, Oregon	Q42022 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	The Dalles, Oregon (2nd facility)	Q42022 Trailing twelve-month (TTM) PUE	1.07	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Henderson, Nevada	Q42022 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Dublin, Ireland	Q42022 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	St. Ghislain, Belgium	Q42022 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Fredericia, Denmark	Q42022 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Eemshaven, Netherlands	Q42022 Trailing twelve-month (TTM) PUE	1.07	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Hamina, Finland	Q42022 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Changua County, Taiwan	Q42022 Trailing twelve-	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/

				month (TTM) PUE			
Google	2022	Single location PUE	Singapore	Q42022 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Singapore (2nd facility)	Q42022 Trailing twelve-month (TTM) PUE	1.21	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2022	Single location PUE	Quilicura, Chile	Q42022 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Fleet-wide PUE	Global	Q42021 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Douglas County, Georgia	Q42021 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Lenoir, North Carolina	Q42021 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Berkeley County, South Carolina	Q42021 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Montgomery County, Tennessee	Q42021 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Jackson County, Alabama	Q42021 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Loudoun County, Virginia (2nd facility)	Q42021 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/

Google	2021	Single location PUE	Loudoun County, Virginia (2nd facility)	Q42021 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Council Bluffs, Iowa	Q42021 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Council Bluffs, Iowa (2nd facility)	Q42021 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Mayes County, Oklahoma	Q42021 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	The Dalles, Oregon	Q42021 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	The Dalles, Oregon (2nd facility)	Q42021 Trailing twelve-month (TTM) PUE	1.06	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Dublin, Ireland	Q42021 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	St. Ghislain, Belgium	Q42021 Trailing twelve-month (TTM) PUE	1.08	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Eemshaven, Netherlands	Q42021 Trailing twelve-month (TTM) PUE	1.08	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Hamina, Finland	Q42021 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Changua County, Taiwan	Q42021 Trailing twelve-	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/

				month (TTM) PUE			
Google	2021	Single location PUE	Singapore	Q42021 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2021	Single location PUE	Quilicura, Chile	Q42021 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Fleet-wide PUE	Global	Q42020 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Douglas County, Georgia	Q42020 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Lenoir, North Carolina	Q42020 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Berkeley County, South Carolina	Q42020 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Council Bluffs, Iowa	Q42020 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Council Bluffs, Iowa (2nd facility)	Q42020 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Mayes County, Oklahoma	Q42020 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	The Dalles, Oregon	Q42020 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/

Google	2020	Single location PUE	The Dalles, Oregon (2nd facility)	Q42020 Trailing twelve-month (TTM) PUE	1.07	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Dublin, Ireland	Q42020 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	St. Ghislain, Belgium	Q42020 Trailing twelve-month (TTM) PUE	1.08	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Eemshaven, Netherlands	Q42020 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Hamina, Finland	Q42020 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Changhua County, Taiwan	Q42020 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Singapore	Q42020 Trailing twelve-month (TTM) PUE	1.14	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2020	Single location PUE	Quilicura, Chile	Q42020 Trailing twelve-month (TTM) PUE	1.08	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Fleet-wide PUE	Global	Q42019 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	Douglas County, Georgia	Q42019 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	Lenoir, North Carolina	Q42019 Trailing twelve-	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/

				month (TTM) PUE			
Google	2019	Single location PUE	Berkeley County, South Carolina	Q42019 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	Council Bluffs, Iowa	Q42019 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	Council Bluffs, Iowa (2nd facility)	Q42019 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	Mayes County, Oklahoma	Q42019 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	The Dalles, Oregon	Q42019 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	The Dalles, Oregon (2nd facility)	Q42019 Trailing twelve-month (TTM) PUE	1.07	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	Dublin, Ireland	Q42019 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	St. Ghislain, Belgium	Q42019 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	Eemshaven, Netherlands	Q42019 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	Hamina, Finland	Q42019 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/

Google	2019	Single location PUE	Changhua County, Taiwan	Q42019 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	Singapore	Q42019 Trailing twelve-month (TTM) PUE	1.15	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2019	Single location PUE	Quilicura, Chile	Q42019 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Fleet-wide PUE	Global	Q42018 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	Douglas County, Georgia	Q42018 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	Lenoir, North Carolina	Q42018 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	Berkeley County, South Carolina	Q42018 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	Council Bluffs, Iowa	Q42018 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	Council Bluffs, Iowa (2nd facility)	Q42018 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	Mayes County, Oklahoma	Q42018 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	The Dalles, Oregon	Q42018 Trailing twelve-	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/

				month (TTM) PUE			
Google	2018	Single location PUE	Dublin, Ireland	Q42018 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	St. Ghislain, Belgium	Q42018 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	Eemshaven, Netherlands	Q42018 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	Hamina, Finland	Q42018 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	Changhua County, Taiwan	Q42018 Trailing twelve-month (TTM) PUE	1.14	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	Singapore	Q42018 Trailing twelve-month (TTM) PUE	1.18	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2018	Single location PUE	Quilicura, Chile	Q42018 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Fleet-wide PUE	Global	Q42017 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	Douglas County, Georgia	Q42017 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	Lenoir, North Carolina	Q42017 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/

Google	2017	Single location PUE	Berkeley County, South Carolina	Q42017 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	Council Bluffs, Iowa	Q42017 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	Council Bluffs, Iowa (2nd facility)	Q42017 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	Mayes County, Oklahoma	Q42017 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	The Dalles, Oregon	Q42017 Trailing twelve-month (TTM) PUE	1.14	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	Dublin, Ireland	Q42017 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	St. Ghislain, Belgium	Q42017 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	Eemshaven, Netherlands	Q42017 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	Hamina, Finland	Q42017 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	Changhua County, Taiwan	Q42017 Trailing twelve-month (TTM) PUE	1.14	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2017	Single location PUE	Singapore	Q42017 Trailing twelve-	1.18	Level 3	https://www.google.com/about/datacenters/efficiency/

				month (TTM) PUE			
Google	2017	Single location PUE	Quilicura, Chile	Q42017 Trailing twelve-month (TTM) PUE	1.14	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Fleet-wide PUE	Global	Q42016 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	Douglas County, Georgia	Q42016 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	Lenoir, North Carolina	Q42016 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	Berkeley County, South Carolina	Q42016 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	Council Bluffs, Iowa	Q42016 Trailing twelve-month (TTM) PUE	1.1	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	Council Bluffs, Iowa (2nd facility)	Q42016 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	Mayes County, Oklahoma	Q42016 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	The Dalles, Oregon	Q42016 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	Dublin, Ireland	Q42016 Trailing twelve-month (TTM) PUE	1.15	Level 3	https://www.google.com/about/datacenters/efficiency/

Google	2016	Single location PUE	St. Ghislain, Belgium	Q42016 Trailing twelve-month (TTM) PUE	1.09	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	Hamina, Finland	Q42016 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	Changhua County, Taiwan	Q42016 Trailing twelve-month (TTM) PUE	1.17	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	Singapore	Q42016 Trailing twelve-month (TTM) PUE	1.2	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2016	Single location PUE	Quilicura, Chile	Q42016 Trailing twelve-month (TTM) PUE	1.11	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2015	Fleet-wide PUE	Global	Q42015 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2014	Fleet-wide PUE	Global	Q42014 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2013	Fleet-wide PUE	Global	Q42013 Trailing twelve-month (TTM) PUE	1.12	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2012	Fleet-wide PUE	Global	Q42012 Trailing twelve-month (TTM) PUE	1.13	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2011	Fleet-wide PUE	Global	Q42011 Trailing twelve-month (TTM) PUE	1.16	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2010	Fleet-wide PUE	Global	Q42010 Trailing twelve-	1.18	Level 3	https://www.google.com/about/datacenters/efficiency/

				month (TTM) PUE			
Google	2009	Fleet-wide PUE	Global	Q42009 Trailing twelve-month (TTM) PUE	1.19	Level 3	https://www.google.com/about/datacenters/efficiency/
Google	2008	Fleet-wide PUE	Global	Q42008 Trailing twelve-month (TTM) PUE	1.21	Level 3	https://www.google.com/about/datacenters/efficiency/
Huawei	2021	Single location PUE	Gui'an, China	Annual Average PUE	1.12	Not Specified	https://www-file.huawei.com/-/media/corp2020/pdf/sustainability/sustainability-report-2021-en.pdf
IBM	2012	Fleet-wide PUE	Global	Annual average PUE	1.73	Not Specified	https://www.ibm.com/ibm/environment/annual/IBMEnvReport_2012.pdf
IBM	2013	Fleet-wide PUE	Global	Annual average PUE	1.73	Not Specified	https://www.ibm.com/ibm/environment/annual/IBMEnvReport_2013.pdf
IBM	2014	Fleet-wide PUE	Global	Annual average PUE	1.71	Not Specified	https://www.ibm.com/ibm/environment/annual/IBMEnvReport_2014.pdf
IBM	2015	Fleet-wide PUE	Global	Annual average PUE	1.71	Not Specified	https://www.ibm.com/ibm/environment/annual/IBMEnvReport_2015.pdf
IBM	2016	Fleet-wide PUE	Global	Annual average PUE	1.69	Not Specified	https://www.ibm.com/ibm/environment/annual/IBMEnvReport_2016.pdf
IBM	2017	Fleet-wide PUE	Global	Annual average PUE	1.66	Not Specified	https://www.ibm.com/ibm/environment/annual/IBMEnvReport_2017.pdf
IBM	2018	Fleet-wide PUE	Global	Annual average PUE	1.76	Not Specified	https://www.ibm.com/ibm/environment/annual/IBMEnvReport_2018.pdf
IBM	2019	Fleet-wide PUE	Global	Annual average PUE	1.7	Not Specified	https://www.ibm.com/ibm/environment/annual/IBMEnvReport_2019.pdf
IBM	2020	Fleet-wide PUE	Global	Annual average PUE	1.67	Not Specified	https://www.ibm.com/ibm/environment/annual/IBMEnvReport_2020.pdf
IBM	2021	Fleet-wide PUE	Global	Annual average PUE	1.53	Not Specified	https://www.ibm.com/impact/files/reports-policies/2021/IBM_2021_ESG_Report.pdf
IBM	2022	Fleet-wide PUE	Global	Annual average PUE	1.52	Not Specified	https://www.ibm.com/impact/files/reports-policies/2022/IBM_2022_ESG_Report.pdf
JD	2021	Fleet-wide PUE	Global	Annual average PUE	1.1	Not Specified	https://ir.jd.com/system/files-encrypted/nasdaq_kms/assets/2022/05/23/14-48-50/2021%20JD.com%20Environmental%20Social%20and%20Governance%20Report%20-20MB.pdf
JD	2020	Fleet-wide PUE	Global	Annual average PUE	1.3	Not Specified	https://ir.jd.com/system/files-encrypted/nasdaq_kms/assets/2021/04/19/2-46-41/2020%20JD.com%20Environmental%20Social%20and%20Governance%20Report.pdf

Mastercard	2022	Fleet-wide PUE	Global	Annual Average PUE	1.39	Not Specified	https://www.mastercard.com/news/perspectives/featured-topics/sustainability/mastercard-esg-report-2022/
Mastercard	2021	Fleet-wide PUE	Global	Annual Average PUE	1.51	Not Specified	https://www.mastercard.com/content/dam/public/mastercardcom/na/global-site/documents/mastercard-sustainability-report-2021.pdf
Mastercard	2020	Fleet-wide PUE	Global	Annual Average PUE	1.5	Not Specified	https://www.mastercard.com/content/dam/public/mastercardcom/na/global-site/documents/mastercard-sustainability-report-2021.pdf
Mastercard	2019	Fleet-wide PUE	Global	Annual Average PUE	1.55	Not Specified	https://www.mastercard.com/content/dam/public/mastercardcom/na/global-site/documents/mastercard-sustainability-report-2021.pdf
Mastercard	2018	Fleet-wide PUE	Global	Annual Average PUE	1.41	Not Specified	https://www.mastercard.com/content/dam/public/mastercardcom/na/global-site/documents/mastercard-sustainability-report-2021.pdf
Meta (Facebook)	2013	Fleet-wide PUE	Global	Annual average PUE	1.09	Not Specified	https://ucsb.app.box.com/file/782313064622?s=osm2o0kjjqtqj3dv6lsysg0oi2pvqr8w
Meta (Facebook)	2014	Fleet-wide PUE	Global	Annual average PUE	1.08	Not Specified	https://ucsb.app.box.com/file/782313064622?s=osm2o0kjjqtqj3dv6lsysg0oi2pvqr8w
Meta (Facebook)	2015	Fleet-wide PUE	Global	Annual average PUE	1.09	Not Specified	https://sustainability.fb.com/wp-content/uploads/2020/12/FB_Sustainability-Data-Disclosure-2019.pdf
Meta (Facebook)	2016	Fleet-wide PUE	Global	Annual average PUE	1.1	Not Specified	https://sustainability.fb.com/report/2020-sustainability-report/
Meta (Facebook)	2017	Fleet-wide PUE	Global	Annual average PUE	1.1	Not Specified	https://sustainability.fb.com/report/2020-sustainability-report/
Meta (Facebook)	2018	Fleet-wide PUE	Global	Annual average PUE	1.11	Not Specified	https://sustainability.fb.com/report/2020-sustainability-report/
Meta (Facebook)	2019	Fleet-wide PUE	Global	Annual average PUE	1.11	Not Specified	https://sustainability.fb.com/report/2020-sustainability-report/
Meta (Facebook)	2020	Fleet-wide PUE	Global	Annual average PUE	1.1	Not Specified	https://sustainability.fb.com/report/2020-sustainability-report/
Meta (Facebook)	2021	Fleet-wide PUE	Global	Annual average PUE	1.09	Not Specified	https://sustainability.fb.com/2021-sustainability-report/
Meta (Facebook)	2022	Fleet-wide PUE	Global	Annual average PUE	1.08	Not Specified	https://sustainability.fb.com/wp-content/uploads/2023/07/Meta-2023-Sustainability-Report.pdf
Microsoft	2021	Fleet-wide PUE	Americas	Annual average PUE	1.17	Not Specified	https://azure.microsoft.com/en-us/blog/how-microsoft-measures-datacenter-water-and-energy-use-to-improve-azure-cloud-sustainability/
Microsoft	2021	Fleet-wide PUE	Asia Pacific	Annual average PUE	1.405	Not Specified	https://azure.microsoft.com/en-us/blog/how-microsoft-measures-datacenter-water-and-energy-use-to-improve-azure-cloud-sustainability/
Microsoft	2021	Fleet-wide PUE	Europe, Middle East, Africa	Annual average PUE	1.185	Not Specified	https://azure.microsoft.com/en-us/blog/how-microsoft-measures-datacenter-water-and-energy-use-to-improve-azure-cloud-sustainability/

Microsoft	2021	Fleet-wide PUE	Global	Annual average PUE	1.18	Not Specified	https://azure.microsoft.com/en-us/blog/how-microsoft-measures-datacenter-water-and-energy-use-to-improve-azure-cloud-sustainability/
Microsoft	2014	Fleet-wide PUE	Global	Annual average PUE	1.4	Not Specified	http://download.microsoft.com/download/3/1/6/316999F9-92F3-4235-BBE5-6C949F521AB9/Microsoft_2014_Citizenship_Report.pdf
Microsoft	2012	Fleet-wide PUE	Global	Annual average PUE	1.4	Not Specified	https://download.microsoft.com/download/0/B/4/0B45C094-CAF2-4909-99FB-897BB65B4815/MS%202012%20Citizenship%20Report.pdf
Naver	2022	Single location PUE	South Korea	Annual Average PUE	1.1	Not Specified	https://www.navercorp.com/navercorp_/ir/sustainabilityReport/NAVER_2022_ESG_ENG.pdf
Naver	2021	Single location PUE	South Korea	Annual Average PUE	1.1	Not Specified	https://www.navercorp.com/navercorp_/ir/sustainabilityReport/NAVER_2021_SASB_ENG.pdf
Naver	2020	Single location PUE	South Korea	Annual Average PUE	1.09	Not Specified	https://www.navercorp.com/navercorp_/ir/sustainabilityReport/NAVER_2021_SASB_ENG.pdf
Naver	2019	Single location PUE	South Korea	Annual Average PUE	1.09	Not Specified	https://www.navercorp.com/navercorp_/ir/sustainabilityReport/NAVER_2021_SASB_ENG.pdf
NextDC	2022	Fleet-wide PUE	Australia	Annual Average PUE	1.38	Not Specified	https://www.nextdc.com/hubfs/23251048/Downloadable%20PDFs/FY22%20Environmental%20Social%20and%20Governance%20Report.pdf
NextDC	2021	Fleet-wide PUE	Australia	Annual Average PUE	1.4	Not Specified	https://www.nextdc.com/hubfs/23251048/Downloadable%20PDFs/FY21%20Environmental%20Social%20and%20Governance%20Report.pdf
NTT Group	2022	Fleet-wide PUE	Global	Annual Average PUE	1.87	Not Specified	
NTT Group	2021	Fleet-wide PUE	Global	Annual Average PUE	1.67	Not Specified	
NTT Group	2020	Fleet-wide PUE	Global	Annual Average PUE	1.65	Not Specified	https://group.ntt/en/csr/data/pdf/esg_report_2021e.pdf
NTT Group	2019	Fleet-wide PUE	Global	Annual Average PUE	1.68	Not Specified	https://group.ntt/en/csr/data/pdf/esg_report_2021e.pdf
NTT Group	2018	Fleet-wide PUE	Global	Annual Average PUE	1.74	Not Specified	https://group.ntt/en/csr/data/pdf/esg_report_2021e.pdf
NTT Group	2017	Fleet-wide PUE	Global	Annual Average PUE	1.72	Not Specified	https://group.ntt/en/csr/data/pdf/esg_report_2021e.pdf
NVIDIA	2018	Fleet-wide PUE	Global	Annual Average PUE	1.52	Not Specified	https://images.nvidia.com/aem-dam/en-zz/Solutions/documents/FY2018-NVIDIA-CSR-Social-Responsibility.pdf
NVIDIA	2017	Fleet-wide PUE	Global	Annual Average PUE	1.56	Not Specified	https://images.nvidia.com/aem-dam/en-zz/Solutions/documents/FY2018-NVIDIA-CSR-Social-Responsibility.pdf
NVIDIA	2016	Fleet-wide PUE	Global	Annual Average PUE	1.58	Not Specified	https://images.nvidia.com/aem-dam/en-zz/Solutions/documents/FY2018-NVIDIA-CSR-Social-Responsibility.pdf

NVIDIA	2015	Fleet-wide PUE	Global	Annual Average PUE	1.57	Not Specified	https://images.nvidia.com/aem-dam/en-zz/Solutions/documents/FY2018-NVIDIA-CSR-Social-Responsibility.pdf
Oracle	2022	Single location PUE	Ashburn, US East	Annual average PUE	1.39	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Chicago, US Midwest	Annual average PUE	2.33	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Phoenix, US West	Annual average PUE	1.36	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	San Jose, US West	Annual average PUE	1.38	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Montreal, Canada Southeast	Annual average PUE	1.31	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Toronto, Canada Southeast	Annual average PUE	1.27	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Ashburn, US Gov East	Annual average PUE	1.41	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Forth Worth, US Gov South	Annual average PUE	2.18	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Phoenix, US Gov West	Annual average PUE	1.38	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Ashburn, US DoD East	Annual average PUE	1.43	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Chicago, US DoD North	Annual average PUE	1.59	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Phoenix, US DoD West	Annual average PUE	1.36	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Sao Paulo, Brazil East	Annual average PUE	1.44	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Vinhedo, Brazil Southeast	Annual average PUE	1.31	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Santiago, Chile	Annual average PUE	1.49	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Queretaro, Mexico Central	Annual average PUE	1.72	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Paris, France Central	Annual average PUE	1.58	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf

Oracle	2022	Single location PUE	Marseille, France South	Annual average PUE	1.13	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Frankfurt, Germany Central	Annual average PUE	1.34	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Milan, Italy Northwest	Annual average PUE	1.35	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Amsterdam, Netherlands Northwest	Annual average PUE	1.27	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Madrid, Spain Central	Annual average PUE	1.5	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Stockholm, Sweden Central	Annual average PUE	1.53	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Zurich, Switzerland North	Annual average PUE	1.34	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	London, UK South	Annual average PUE	1.35	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Newport, UK West	Annual average PUE	1.4	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	London, UK Gov South	Annual average PUE	1.33	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Newport, UK Gov West	Annual average PUE	1.4	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Jerusalem, Israel East	Annual average PUE	1.8	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Abu Dhabi, UAE	Annual average PUE	1.51	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Dubai, UAE East	Annual average PUE	1.84	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Sydney, Australia East	Annual average PUE	1.3	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Melbourne, Australia Southeast	Annual average PUE	1.34	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Hyderabad, India South	Annual average PUE	1.72	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Mumbai, India West	Annual average PUE	1.85	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf

Oracle	2022	Single location PUE	Osaka, Japan Central	Annual average PUE	1.33	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Tokyo, Japan East	Annual average PUE	1.37	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Singapore, Singapore	Annual average PUE	1.43	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Seoul, South Korea Central	Annual average PUE	1.58	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2022	Single location PUE	Chuncheon, South Korea North	Annual average PUE	1.27	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Ashburn, US East	Annual average PUE	1.41	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Phoenix, US West	Annual average PUE	1.49	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	San Jose, US West	Annual average PUE	1.39	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Toronto, Canada Southeast	Annual average PUE	1.22	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Montreal, Canada Southeast	Annual average PUE	1.12	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Phoenix, US Gov West	Annual average PUE	1.36	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Ashburn, US DoD East	Annual average PUE	1.5	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Phoenix, US DoD West	Annual average PUE	1.36	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Sao Paulo, Brazil East	Annual average PUE	1.3	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Vinhedo, Brazil Southeast	Annual average PUE	1.41	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Frankfurt, Germany Central	Annual average PUE	1.41	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	London, UK South	Annual average PUE	1.62	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Newport, UK West	Annual average PUE	1.5	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf

Oracle	2021	Single location PUE	Amsterdam, Netherlands Northwest	Annual average PUE	1.16	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Zurich, Switzerland North	Annual average PUE	1.49	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Marseille, France South	Annual average PUE	1.3	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Milan, Italy Northwest	Annual average PUE	1.35	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	London, UK Gov South	Annual average PUE	1.71	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Newport, UK Gov West	Annual average PUE	1.54	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Sydney, Austrailia East	Annual average PUE	1.38	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Melbourne, Austrailia Southeast	Annual average PUE	1.34	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Tokyo, Japan East	Annual average PUE	1.51	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Seoul, South Korea Central	Annual average PUE	1.49	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Chuncheon, South Korea North	Annual average PUE	1.17	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Hyderabad, India South	Annual average PUE	1.75	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2021	Single location PUE	Mumbai, India West	Annual average PUE	1.78	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Ashburn, US East	Annual average PUE	1.41	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Phoenix, US West	Annual average PUE	1.49	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	San Jose, US West	Annual average PUE	1.39	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Toronto, Canada Southeast	Annual average PUE	1.22	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Montreal, Canada Southeast	Annual average PUE	1.12	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf

Oracle	2020	Single location PUE	Phoenix, US Gov West	Annual average PUE	1.36	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Ashburn, US DoD East	Annual average PUE	1.5	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Phoenix, US DoD West	Annual average PUE	1.36	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Sao Paulo, Brazil	Annual average PUE	1.3	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Vinhedo, Brazil	Annual average PUE	1.41	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Frankfurt, Germany	Annual average PUE	1.41	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	London, UK	Annual average PUE	1.62	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Newport, UK	Annual average PUE	1.5	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Amsterdam, Netherlands	Annual average PUE	1.16	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Zurich, Switzerland	Annual average PUE	1.49	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Marseille, France South	Annual average PUE	1.3	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Milan, Italy Northwest	Annual average PUE	1.35	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	London, UK Gov	Annual average PUE	1.71	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Newport, UK Gov	Annual average PUE	1.54	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Sydney, Australia	Annual average PUE	1.38	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Melbourne, Australia	Annual average PUE	1.34	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Tokyo, Japan	Annual average PUE	1.51	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Seoul, South Korea	Annual average PUE	1.49	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf

Oracle	2020	Single location PUE	Chuncheon, South Korea	Annual average PUE	1.17	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Hyderabad, India	Annual average PUE	1.75	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2020	Single location PUE	Mumbai, India	Annual average PUE	1.78	Not Specified	https://www.oracle.com/a/ocom/docs/corporate/citizenship/clean-cloud-oci.pdf
Oracle	2014	Single location PUE	Utah, US	Annual average PUE	1.3	Not Specified	Oracle Corporate Citizenship report, 2014, page 61
Oracle	2012	Single location PUE	Utah, US	Annual average PUE	1.3	Not Specified	Oracle Corporate Citizenship report, 2012, page 61
QTS	2022	Fleet-wide PUE	Europe	Annual average PUE	1.68	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/qts_sustainability-report_2022.ashx
QTS	2022	Fleet-wide PUE	U.S	Annual average PUE	1.46	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/qts_sustainability-report_2022.ashx
QTS	2021	Fleet-wide PUE	Europe	Annual average PUE	1.7	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/2021-esg-report.ashx
QTS	2021	Fleet-wide PUE	U.S	Annual average PUE	1.46	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/2021-esg-report.ashx
QTS	2020	Fleet-wide PUE	Europe	Annual average PUE	1.79	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/2020-esg-initiatives-report_.ashx
QTS	2020	Fleet-wide PUE	U.S	Annual average PUE	1.49	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/2020-esg-initiatives-report_.ashx
QTS	2020	Fleet-wide PUE	US	Annual Average PUE	1.49	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/2020-esg-initiatives-report.pdf
QTS	2020	Fleet-wide PUE	Europe	Annual Average PUE	1.79	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/2020-esg-initiatives-report.pdf
QTS	2021	Fleet-wide PUE	US	Annual Average PUE	1.46	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/2021-esg-report.ashx
QTS	2021	Fleet-wide PUE	Europe	Annual Average PUE	1.7	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/2021-esg-report.ashx
QTS	2022	Fleet-wide PUE	US	Annual Average PUE	1.46	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/qts_sustainability-report_2022.pdf
QTS	2022	Fleet-wide PUE	Europe	Annual Average PUE	1.68	Not Specified	https://www.qtsdatacenters.com/-/media/files/sustainability-reports/qts_sustainability-report_2022.pdf
Salesforce	2022	Fleet-wide PUE	Global	Annual average PUE	1.42	Not Specified	https://stakeholderimpactreport.salesforce.com/pdf/FY23-SIR-Summary-ESG-Metrics.pdf

Salesforce	2021	Fleet-wide PUE	Global	Annual average PUE	1.42	Not Specified	https://stakeholderimpactreport.salesforce.com/pdf/FY21-SIR-Summary-ESG-Metrics-And-Indicators.pdf
Salesforce	2020	Fleet-wide PUE	Global	Annual average PUE	1.39	Not Specified	https://www.salesforce.com/content/dam/web/en_us/www/documents/white-papers/FY20-stakeholder-impact-report.pdf
Salesforce	2019	Fleet-wide PUE	Global	Annual average PUE	1.4	Not Specified	https://www.salesforce.com/content/dam/web/en_us/www/documents/reports/sustainability-FY19-stakeholder-impact-report.pdf
Salesforce	2018	Fleet-wide PUE	Global	Annual average PUE	1.41	Not Specified	https://www.salesforce.com/content/dam/web/en_us/www/documents/reports/sustainability-FY18-stakeholder-impact-report.pdf
Salesforce	2017	Fleet-wide PUE	Global	Annual average PUE	1.45	Not Specified	https://www.salesforce.com/content/dam/web/en_us/www/documents/datasheets/sfdc-fy17-stakeholder-impact.pdf
Salesforce	2016	Fleet-wide PUE	Global	Annual average PUE	1.45	Not Specified	https://www.salesforce.com/content/dam/web/en_us/www/assets/pdf/datasheets/sustainability-report-fy1516.pdf
Salesforce	2015	Fleet-wide PUE	Global	Annual average PUE	1.42	Not Specified	https://www.salesforce.com/content/dam/web/en_us/www/assets/pdf/datasheets/sustainability-report-fy1516.pdf
Salesforce	2014	Fleet-wide PUE	Global	Annual average PUE	1.43	Not Specified	https://www.salesforce.com/content/dam/web/en_us/www/assets/pdf/datasheets/sustainability-report-fy1314.pdf
Salesforce	2013	Fleet-wide PUE	Global	Annual average PUE	1.45	Not Specified	https://www.salesforce.com/content/dam/web/en_us/www/assets/pdf/datasheets/sustainability-report-fy1314.pdf
Salesforce	2012	Fleet-wide PUE	Global	Annual average PUE	1.47	Not Specified	https://www.salesforce.com/content/dam/web/en_us/www/assets/pdf/datasheets/sustainability-report-fy12.pdf
SAP	2022	Fleet-wide PUE	Global - internal data centers	Annual Average PUE of internal data centers	1.38	Not Specified	https://www.sap.com/integrated-reports/2022/en/environmental-performance.html?pdf-asset=8230868e-647e-0010-bca6-c68f7e60039b&page=114#energy
SAP	2022	Fleet-wide PUE	Global - external data centers	Annual Average PUE of external data centers	1.55	Not Specified	https://www.sap.com/integrated-reports/2022/en/environmental-performance.html?pdf-asset=8230868e-647e-0010-bca6-c68f7e60039b&page=114#energy
SAP	2021	Fleet-wide PUE	Global - internal data centers	Annual Average PUE of internal data centers	1.38	Not Specified	https://www.sap.com/docs/download/investors/2021/sap-2021-integrated-report.pdf
SAP	2021	Fleet-wide PUE	Global - external data centers	Annual Average PUE of external data centers	1.55	Not Specified	https://www.sap.com/docs/download/investors/2021/sap-2021-integrated-report.pdf

SAP	2020	Fleet-wide PUE	Global - internal data centers	Annual Average PUE of internal data centers	1.41	Not Specified	https://www.sap.com/docs/download/investors/2020/sap-2020-integrated-report.pdf
SAP	2020	Fleet-wide PUE	Global - external data centers	Annual Average PUE of external data centers	1.59	Not Specified	https://www.sap.com/docs/download/investors/2020/sap-2020-integrated-report.pdf
SAP	2019	Fleet-wide PUE	St. Leon-Rot, Germany	Annual Average PUE	1.36	Not Specified	https://www.sap.com/integrated-reports/2019/en.html
SAP	2019	Fleet-wide PUE	Global	Annual Average PUE of external data centers	1.58	Not Specified	https://www.sap.com/integrated-reports/2019/en.html
SAP	2018	Fleet-wide PUE	Global	Annual Average PUE of external data centers	1.61	Not Specified	https://www.sap.com/docs/download/investors/2018/sap-2018-integrated-report.pdf
SAP	2017	Fleet-wide PUE	Global	Annual Average PUE of external data centers	1.6	Not Specified	https://www.sap.com/docs/download/investors/2017/sap-2017-integrated-report.pdf
Splunk	2022	Fleet-wide PUE	Global	Annual Average PUE	1.54	Not Specified	https://www.splunk.com/en_us/pdfs/global-impact/2022-global-impact-report.pdf
Splunk	2021	Fleet-wide PUE	Global	Annual Average PUE	1.39	Not Specified	https://www.splunk.com/en_us/pdfs/global-impact/2022-global-impact-report.pdf
Switch	2022	Fleet-wide PUE	Global	Annual average PUE	1.18	Not Specified	https://www.switch.com/sustainability/
Switch	2020	Fleet-wide PUE	United States	Seasoned Sectors 12 month trailing average	1.23	Not Specified	https://www.switch.com/sustainability/
Tencent	2022	Fleet-wide PUE	Global	Annual average PUE	1.298	Not Specified	https://static.www.tencent.com/uploads/2023/04/06/2efdae398c746523320cbb7660e5fafa.pdf
Tencent	2021	Fleet-wide PUE	Global	Annual average PUE	1.317	Not Specified	https://static.www.tencent.com/uploads/2023/04/06/2efdae398c746523320cbb7660e5fafa.pdf

Tencent	2020	Fleet-wide PUE	Mainland China	Annual average PUE	1.32	Not Specified	https://static.www.tencent.com/uploads/2022/02/11/8145567c7560456eec481d512d4429c8.pdf
Tencent	2019	Fleet-wide PUE	Mainland China	Annual average PUE	1.35	Not Specified	https://static.www.tencent.com/uploads/2022/02/11/8145567c7560456eec481d512d4429c8.pdf
Tencent	2018	Fleet-wide PUE	Mainland China	Annual average PUE	1.37	Not Specified	https://static.www.tencent.com/uploads/2022/02/11/8145567c7560456eec481d512d4429c8.pdf
Tencent	2017	Fleet-wide PUE	Mainland China	Annual average PUE	1.5	Not Specified	
VISA	2017	Fleet-wide PUE	Global	Annual Average PUE	1.84	Not Specified	https://usa.visa.com/content/dam/VCOM/regional/na/us/about-visa/documents/2022-environmental-social-governance-report.pdf
VISA	2018	Fleet-wide PUE	Global	Annual Average PUE	1.67	Not Specified	https://usa.visa.com/content/dam/VCOM/regional/na/us/about-visa/documents/2022-environmental-social-governance-report.pdf
VISA	2019	Fleet-wide PUE	Global	Annual Average PUE	1.63	Not Specified	https://usa.visa.com/content/dam/VCOM/regional/na/us/about-visa/documents/2022-environmental-social-governance-report.pdf
VISA	2020	Fleet-wide PUE	Global	Annual Average PUE	1.56	Not Specified	https://usa.visa.com/content/dam/VCOM/regional/na/us/about-visa/documents/2022-environmental-social-governance-report.pdf
VISA	2021	Fleet-wide PUE	Global	Annual Average PUE	1.52	Not Specified	https://usa.visa.com/content/dam/VCOM/regional/na/us/about-visa/documents/2022-environmental-social-governance-report.pdf
VISA	2022	Fleet-wide PUE	Global	Annual Average PUE	1.48	Not Specified	https://usa.visa.com/content/dam/VCOM/regional/na/us/about-visa/documents/2022-environmental-social-governance-report.pdf
VMWare	2022	Single location PUE	East Wenatchee, WA, US	Annual average PUE	1.29	Not Specified	https://www.vmware.com/content/dam/digitalmarketing/vmware/en/pdf/docs/vmware-esg-report-2022.pdf
VMWare	2021	Single location PUE	East Wenatchee, WA, US	Annual average PUE	1.29	Not Specified	https://www.vmware.com/content/dam/digitalmarketing/vmware/en/pdf/company/vmware-esg-report-2021.pdf
VMWare	2020	Single location PUE	East Wenatchee, WA, US	Annual average PUE	1.28	Not Specified	https://www.vmware.com/content/dam/digitalmarketing/vmware/en/pdf/sustainability/vmware-global-impact-report-2020.pdf
VMWare	2019	Single location PUE	East Wenatchee, WA, US	Annual average PUE	1.27	Not Specified	https://www.vmware.com/content/dam/digitalmarketing/vmware/en/pdf/company/vmware-esg-global-impact-report-2019.pdf
VMWare	2021	Single location PUE	East Wenatchee, WA, US	Annual average PUE	1.29	Not Specified	https://www.vmware.com/content/dam/digitalmarketing/vmware/en/pdf/company/vmware-esg-report-2021.pdf
VMWare	2022	Single location PUE	East Wenatchee, WA, US	Annual average PUE	1.29	Not Specified	https://www.vmware.com/content/dam/digitalmarketing/vmware/en/pdf/docs/vmware-esg-report-2022.pdf
VMWare	2023	Single location PUE	East Wenatchee, WA, US	Annual average PUE	1.29	Not Specified	https://www.vmware.com/content/dam/digitalmarketing/vmware/en/pdf/docs/vmware-esg-report-2023.pdf
Z-Holdings	2022	Fleet-wide PUE	Global	Annual average PUE	1.33	Not Specified	https://www.z-holdings.co.jp/en/sustainability/stakeholder/esg/

Z-Holdings	2021	Fleet-wide PUE	Global	Annual average PUE	1.36	Not Specified	https://www.z-holdings.co.jp/en/sustainability/stakeholder/esg/
Z-Holdings	2020	Fleet-wide PUE	Global	Annual Average PUE	1.38	Not Specified	https://www.z-holdings.co.jp/en/sustainability/stakeholder/esg/#anc1
Z-Holdings	2019	Fleet-wide PUE	Global	Annual Average PUE	1.41	Not Specified	https://www.z-holdings.co.jp/en/sustainability/stakeholder/esg/#anc1
Z-Holdings	2018	Fleet-wide PUE	Global	Annual Average PUE	1.41	Not Specified	https://www.z-holdings.co.jp/en/sustainability/stakeholder/esg/#anc1
Z-Holdings	2017	Fleet-wide PUE	Global	Annual Average PUE	1.56	Not Specified	https://ucsb.app.box.com/file/762498325003

Policy brief

Harnessing the sufficiency potential in global climate mitigation pathways of IPCC AR6 SPM with a temperature target of 1.5°C by the end of the century

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Executive summary

The potential to reduce global and regional greenhouse gas emissions through sufficiency policies is not captured by the global climate mitigation scenarios that limit warming to 1.5°C in 2100. IPCC AR6 database includes 230 emission scenarios compatible with the 1.5°C climate target, out of which 97 scenarios have no or limited overshoot. The pathways developed under these scenarios do not include sufficiency assumptions to avoid up-front the demand for all natural resources while delivering wellbeing for all within the planetary boundaries. The overlooked sufficiency policies in these global scenarios give a hope about the capacity of humanity to decarbonise the world economy while limiting the damage cause by climate change.

Harnessing the sufficiency potential will lead to implementing the principle of common but differentiated responsibilities of countries in climate change. Existing global scenarios are agnostic to this principle. They do not consider cumulative emissions of each country and region in their projections of carbon neutrality targets. Planetary boundaries, the upper limit of sufficiency, require considering a fair share of the remaining carbon budget based on cumulative emissions. This will lead to accelerating the decarbonisation of the global north. If sufficiency would be considered, the G7 countries would become carbon neutral before 2030 and the G20 countries by 2035. Capturing the sufficiency potential will reduce the cost of the decarbonisation and lead to a peaceful global governance as less resources will be needed.

Harnessing the sufficiency potential will make sustainable development goals achievable in all countries. Wellbeing for all, the lower limit of sufficiency, is another principle ignored by the existing global scenarios that limit warming to 1.5°C in 2100. North/South convergence in the access to decent living standard through modern amenities, clean and efficient technologies and services is overlooked in all the pathways assessed. Furthermore, per-capita emissions in the global north are projected to continue to be higher than those in the global south when both regions will be decarbonised. Low-energy demand scenario considers north/south convergence. However, the starting point of this scenario does not match with the data available for both regions.

Capturing the sufficiency potential requires a new modelling framework different from the current SSP-RCP framework considered by the IPCC. The existing modelling framework is based on short-term cost-optimisation without feedback loops. Thus, leading to a shallow, linear and step by step approach to decarbonisation. To the contrary, modelling sufficiency requires considering the overall ecosystem that sustain life on the planet. Early investigation of various modelling approaches suggests applying system dynamic method to harness sufficiency. Funding agencies have an important role to play in shifting the climate modelling community to unlock IPCC AR7 from scenarios that extend inequalities and unfairness that goes back to the colonial time.