令和６年度

地球温暖化対策技術・エネルギー等分析・評価国際連携事業費

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７年３月

公益財団法人 地球環境産業技術研究機構

令和６年度
地球温暖化対策技術・エネルギー等分析・評価国際連携事業費
（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るが、世界のあらゆる国、様々な部門に影響を与える一方で、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。こうした状況を踏まえ、昨年11月の第28回国連気候変動枠組条約締約国会議（COP28）で実施されたパリ協定の世界全体の実施状況を確認する「グローバルストックテイク（GST）」の決定では、ネットゼロという共通の目標に向けて、あらゆるエネルギーや脱炭素技術を活用することに言及しており、真に有効な対策を実現するためには、各国・各部門の様々な状況を考慮することが重要と考えられる。

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、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。特に、気候変動に関する政府間パネル（IPCC）の第6次評価報告書（AR6）で初めて取り上げられたエネルギー需要サイドの評価は、定量的かつ包括的な分析は未だに十分にはなされていない状況であり、次の第7次評価報告書（AR7）の執筆期間において、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。

本事業では、最新の科学的知見や国際交渉の動向も踏まえながら、①エネルギー需要サイドの技術革新と、②それに基づき生じる社会変化、③さらにそのCO_2排出削減への影響等について調査、分析、評価を行うとともに、④国際研究コミュニティの構築を通して、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なった。これらにより、気候政策分析に関する最先端の需要モデルを進展させ、国際的に展開し、IPCCのAR7へインプットしていくことを目的とした。

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 ＬＥＤ（Low Energy Demand）シナリオに基づき、技術革新がもたらすCO_2排出量削減や各産業分野におけるエネルギー需要の変化について、コンピュータモデルを活用し、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・LEDシナリオの国際研究コミュニティの構築及び運営

（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。

研究連携の強化のため、協力関係にある以下の国際研究機関を訪問した。
・国際応用システム分析研究所（IIASA）への訪問：10月のEDITS年次会合時にALPS業務と併せて、オーストリア（ラクセンブルク）に出張をし、研究内容の共有、比較分析、評価に関する進め方について議論を行った。国際的なシナリオ分析等の最新の研究動向についても調査を行った。
・Asian Institute of Technology（AIT）への訪問：10月のEDITS年次会合および10月にパタヤで行われたICUEの国際会議にあわせ、AIT関係者と需要サイドの分析の方針などを議論した。また、最新のアジアを中心とした研究動向を調査した。

協力関係にある国際機関、研究機関、大学等が参加するLEDシナリオの国際研究コミュニティの構築及び運営、コミュニティに参加する機関については、契約時に機関名、研究内容を一覧にした上で、経済産業省産業技術環境局地球環境対策室と相談し決定した。（以下ページにある「付表1 国際ワークショップの参加者リスト」参照）。

（詳細については各研究機関の報告書を参照）
① RITE においては、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。また、ITF-OECD などと連携して道路交通部門におけるシェアリングエコノミーの効果についてモデルを用いたシナリオの比較評価を行った。

② 米国のローレンスバークレー国立研究所 (LBNL)は、エネルギー効率と区別しながら、エネルギー充足の概念とモデル化を行った。この論文では、エネルギー自給率のモデル化を改善するための分散化、適正規模化と削減、利用/タイミングと寿命、多機能性、代替、共有 (DRUMSS) フレームワークを紹介した。 また、今年度の進捗報告として、需要側のデータベースの整理と説明を行った。

③ オーストリアのBOKU は、世界中の適切な生活水準のための物質のストックとフローの研究を行った結果、社会経済的物質的備蓄のわずかな増加は、世界的にある一定の生活水準を確保できることが判明した。また、循環型経済は気候を救うことができるについて、世界的な証拠のレビューを実施した。

④ 英国のプリマス大学は、需要の減少による利益の増加 - 住宅建築部門におけるエネルギー需要対策の相乗効果の定量化についてまとめた。グローバルサウス（インドなど）とグローバルノース（英国な

ど）の代表的な国における、1つの特定の気候変動緩和策（低エネルギー需要対策-LEDシナリオ）である高効率ビル改修から生じる健康、エネルギー安全保障、雇用に関連するコベネフィットを特定、定量化、および金銭化し、需要側のソリューションがユーザー レベルで利益をもたらし、限定的ではあるものの燃料への影響も改善することを示した。

⑤ 中国の清華大学は、水素製鋼技術と従来の長工程および短工程製鋼技術の鉄鋼1トンあたりのライフサイクル全体にわたる炭素排出量の比較と素製鋼技術の1トンあたりの生産コストの分析を含む中国鉄鋼業界の水素サプライチェーン全体の炭素排出量とコスト分析を実施した。

⑥ ブラジルのリオデジャネイロ連邦大学(COPPE) は、ブラジルの需要側エネルギー効率：相互接続された電力システムにおける一日あたりの電力需要に対する熱波の影響評価を行った。この研究では、10年間にわたってブラジルの201か所で観測されたHWイベントの包括的なデータセットを構築し、計量経済モデルを適用して、ブラジル相互接続電力システムの各サブシステムについて、日常の電力消費への影響の定量化を行った。

⑦ 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: CCSへの依存を減らすためのLEDSの可能性と、LEDS における生産ベースおよび消費ベースの炭素価格設定の影響について4つのシナリオで研究を行った。

⑧ ドイツのライナー・ルモワン・インスティテュート(RLI)は、最低限の移動ニーズの定量化に取り組んだ。現在、これらの条件は満たされておらず、必須、十分、または最低限の移動レベルを構成するものについての明確な定義はないため、確立された人間の基本的ニーズの理論に基づいて、乗客の移動を供給とニーズの満足の連鎖の中に明確に位置付け、「適切な移動」を定義した。

⑨ オランダのユトレヒト大学は、データギャップを解消して、低エネルギー需要経路の評価を改善することを目的として需要側の緩和ソリューション: データの現状、機会、今後の方向性の分析を行った。
建物、輸送、食品、産業、都市の5つの主要セクターにわたる需要関連データの可用性のマッピングを行い、回避-シフト-改善(ASI)フレームワークを使用して、緩和戦略を分類し、社会文化、インフラストラクチャ、および技術の変更の機会の特定を行った。

⑩ ハンガリーの中央ヨーロッパ大学 (DBH InnoHub)は、さまざまな政策枠組みの下で脱炭素化を促進するための建築部門における行動対策の可能性を探った。既存の高効率建築 (HEB) モデル内で、充足と行動の変化という 2つの新しいシナリオを開発し、グローバル北半球とグローバル南半球の両国への潜在的な影響の評価を実施した。

⑪ タイのアジア工科大学（AIT）は、南アジアと東南アジアに特に焦点を当てた、需要側ソリューション

の分野横断的な緩和ポテンシャルの方法、データ、推定を行った。また、重要なインフラとしての分散型太陽エネルギーによるコミュニティの回復力の向上 - 南アジアのケーススタディを紹介する。 需要側の気候変動緩和の現状と方向性に関しても説明を行った。

⑫ スイスのEPFLは、スイスのウェルビーイングを確保するためのエネルギー要件と豊かさと不平等の余地について研究を行った。また、2040 年までにスイスの住宅を変革するためのシステム展望: ウェルビーイング、共有スペース、充足感、スプロール化の解消についても地球の限界内ですべての人々のウェルビーイングという価値観に基づいて、2100年までの全国的な新築禁止と、同時に近隣規模の4つの介入を組み合わせた規範的なシナリオの提案を紹介した。

⑬ 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モデル補完性演習について昨年に続き、輸送部門の脱炭素化における共有モビリティの潜在的な影響、特にモーダルシフトの影響を評価することを目的に、IAMモデル間で共有モビリティを展開した場合のシステムレベルの影響を比較する方法を取りまとめた。それにより、輸送モーダル シフトの直接的および体系的な影響をより深く理解して、エネルギーシステムポリシーに情報を提供する方法が調査可能となる。

⑭ フランスのITF-OECDは、先進国などでは車両群のダイナミクスの地域差を考慮することが非常に重要であることを強調し、効果的な脱炭素化政策の形成における地域格差の役割を強調した。また、エネルギーサービスに焦点を当て、建物、輸送、食品、産業の 4つのエンドユーザー セクター、それらのエネルギーとCO_2 排出量の削減の可能性、金銭的コストに関する洞察を行い、需要側の解決策を通じて気候変動を緩和すると、社会への負担が軽減されることを示した。

⑮ イタリアの欧州地中海気候変動センター(CMCC)は、2022年にヨーロッパを襲ったエネルギー危機からEUが提案したエネルギー市場改革の柱の1つは、固定価格小売契約の利用可能性を高めることで、再生可能エネルギーへのアクセスが徐々に増加すると予想されるため、固定価格はエネルギー危機に対する長期的な対応戦略の一部とみなされる。そこでイタリアの電力会社の高頻度消費および請求データを使用して、価格が高騰している期間中に固定価格契約から変動価格契約に変更された消費者行動の調査を行った。

⑯ イギリスのオックスフォード大学では、先進3カ国における技術導入率とそれに伴うコストへの影響が所得10%ごとにどのように異なるかを分析した。世帯レベルの調査データを使用したところ、10%ごとの技術採用率と消費量を予測したところ、採用のタイミングがエネルギーコストの変化の大きさと分布の両方に大きく影響することがわかった。観察されたパターンは、採用を加速することを目的とした政策介入では、エネルギー負担のギャップが拡大しないように、低所得世帯の経済的制約に対処する必要があることを示した。

⑰ ポルトガルのIscte – リスボン大学研究所は、エネルギー需要分析における構造変化を推定する新しい方法論を提示した。それにより、エネルギー政策に大きな意味を持ち、世界、セクター、サブセクター（カテゴリ）レベルでの変化が全体的なエネルギー需要と持続可能性の傾向にどのように影響するかをより正確に評価できることを示した。

⑱ アメリカのウィスコンシン大学マディソン校は、行動、ビジネスモデル、制度的イノベーションを網羅し、採用者が家庭から企業、政府まで多岐にわたる27の社会イノベーションのサンプルの歴史的普及を特徴付ける時系列データを収集して標準化し、時系列データをコンパイルして、各SIの20の追加指標セットを測定した。それにより、社会的イノベーションのサンプル内では普及速度に大きなばらつきがあることがわかった。

⑲ オランダのフローニンゲン大学は、商品、輸送、暖房の3つのセクターにおける需要側と供給側の戦略の受容性を人々がどのように評価するかを調査することを目的に、持続可能なライフスタイルが自分たちのウェルビーイングにどのような影響を与えると人々は考えているのか調査を行った。また、どの要因が戦略の受容性を予測するかも研究を行った。

⑳ アメリカのカリフォルニア大学サンタバーバラ校は、データセンターのエネルギー使用を規制するための新しい政策環境を一覧にして評価し、データセンターのエネルギーと水のつながりの確認を行った。また、この研究では、地方レベルと国家レベルで27の異なるデータセンターポリシーを特定して評価し、今後のエネルギー需要を形成する可能性のある70を超えるさまざまなポリシー属性のデータセットを作成した。

㉑ オーストリアの国際応用システム分析研究所 (IIASA)は、EDITSの活動、成果、年次会合の概要をまとめた。また、EDITSコミュニティの能力開発とネットワークの構造についての解説、研究のハイライトやビルディンググループの活動、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 大阪大学は、今年度のプロジェクト報告書として、日本全国を対象として開発されてきたボトムアップ型の家庭部門最終エネルギー需要予測モデルの推計対象を世界各国に拡張し世界の人々がウェルビーイングな生活を営むために最低限必要なエネルギー需要を推計した。さらに，家庭部門のエネルギー消費用途の中で，大きな割合を占める冷暖房・給湯需要については，外気温と比較することによって推計結果の検証を行った。加えて、LED シナリオで描かれている大幅なエネルギー需要の削減を建築分野において実現するための建築性能シミュレーションの役割について、取りまとめた。

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）比較研究の論文の執筆、情報発信によるIPCC報告書へのインプット

IPCC第七次評価サイクルにおいて報告書への掲載を目指すため、（２）で行った調査、分析、評価について、論文の執筆を行い、IPCCの執筆者を巻き込みながらLEDＤシナリオ等のインプット等必要な対応を以下の通り実施した。

今年度のEDITSプロジェクトにおける投稿論文数は、目標（15件）を大きく上回る件数（4月に別途報告予定）となり、EDITSプロジェクトの成果が明らかに表れてきている。また、国際会議であるEEDAL24の学会に参加し、主要関係者からの情報収集も行なった。

また、EDITSワークショップの参加者には、多くのIPCC執筆者も含まれる（国際ワークショップ概要の「付表1 国際ワークショップの参加者リスト」参照）。 例えば、IPCC第6次評価報告書において、統括執筆責任者(CLA)5名、代表執筆者(LA)15名、また、WGIIIの副議長と査読編集者(RE)と兼任しているDiana Urge-Vorsatz氏は、また同じく副議長と代表執筆者と兼任しているSiir Kilkis氏の出席があった。 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。

また、COP29の開催期間（11月11日―11月22日）内にアゼルバイジャン共和国（バクー）にて日本パビリオンでのサイドイベントも開催し、研究者5名（外部専門家4名含む）を派遣した。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

LED シナリオの国際研究コミュニティに参加する欧州や米国、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、大学等による国際ワークショップをオーストリア　ラクセンブルグにあるIIASA にてハイブリッド形式で開催し、エネルギー需要部門の分析に関する情報交換、研究内容の共有を行った。コアな会議は、10 月 8 日(火)から 10 日(木)まで、サイドイベントは、10/7(月)と10/11(金)にファーストトラック(FT)やワーキンググループ(WG)の会議を実施した。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。また、航空機やホテルにおいて、経済的・利便性・効率性を考慮した上で、経済的に進めた。

また、WG および 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(18 回～)の会議が年間を通じて行われ、四半期ごとに少なくとも 2～4 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、研究内容の共有を行った。

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。

2024 Annual EDITS Meeting
Improving wellbeing while avoiding dangerous climate change
2024年10月8日～11月10日

背景

EDITS が焦点を当てようとしている問題は両面的であり、それは単純化して言えば消費回廊（持続可能な消費の最小値と最大値の幅）と表現される。気候変動の緩和に焦点を当て、気候モデルとエネルギーシステムモデルを使用して、エネルギー需要が大幅に低下して気候の大きな変化を抑制することができる未来を探索し、説明してきた。このフレームワークでは、政策決定のよい結果をもたらす領域である他の中でも、ウェルビーイングを共同利益として使用した（消費回廊の最大値に焦点）。しかし、人間のニーズにより重点を置きウェルビーイングを分析の焦点と見なし気候緩和が共同利益になる方法に重点を置くようになった。すわなち、消費回廊の最小値にも焦点を当て、最大値とあわせて、消費回廊として検討を深めるよう変化してきた。

各国の気候緩和対策とコストには大きな違いがあり、公平性の観点から負担を分担する国も異なる。行動と目標のギャップを理解し、そのギャップを埋めるために何が必要かをより明確に定義する必要性に応えて、2023 年 11 月の第 28 回国連気候変動枠組条約締約国会議 (COP28)で初のグローバル・ストックテイク (GST)が採択された。各国は、ネットゼロという共通目標に向けて、公平性と公正性を確保しながら、またすべてのエネルギーと脱炭素化技術と社会的イノベーションや構造変化などその他の変化を活用しながら、化石燃料の段階的廃止を含む効果的な行動を遅滞なく強化し、活用する必要があることに同意している。真に効果的な対策を達成するには、各国とセクターのさまざまな状況を考慮することが重要である。

それどころかウェルビーイングはより普遍的である。世界中の人々が同じレベルの供給にアクセスできる必要があり、すべての人のニーズを満たす平等性の向上は、気候変動やその他の環境の境界に取り組むためのより公正なシステムにつながると期待される。このため、EDITS のシナリオと理論的研究は、消費回廊の概念と整合し、必要量 (つまり、十分量) を超える過剰消費を制限しながら、誰もが適切な生活水準と良好な生活にアクセスできるようにする必要がある。

需要側の行動と解決策は、人々のために改善を刻み込むと同時に、持続可能性に向けたシステム全体の変革を活用することができる。ウェルビーイングの向上、不平等の削減、安全性の向上は価値体系の中心であり、したがって決定の最終目標であるべきである。供給側とインフラへの相乗効果により、需要側の変革は気候緩和と適応の大きなメリットももたらす。需要側の対策は、特に供給側の対策と比較すると、一般に信じられていることとは反対に、より簡単、より迅速、より低コストで実施されることが多いことが示されているが、再確認する必要がある。

概要

2024 年 EDITS 年次会議は、日本の経済産業省（METI）の資金援助を受けて、国際応用システム分析研究所（IIASA）と地球環境産業技術研究機構（RITE）が共催した。出席者は、全部で 96 名、19 か国 45 機関から 89 名が実開催のワークショップに出席し、7 名はオンラインで参加した。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、過去最高の出席者数となった。60%がヨーロッパからの参加者で、30%がアジアから、7%がアメリカ、2%が南米・その他地域からの参加者であった。

2024 年度 EDITS 年次会議は、イニシアチブにおける共同研究とモデリングの基本的な基盤も目的に開催された。よって、この会議では深い議論のためのフォーラムを提供し、他方では特定のワークフローを強化する場を提供した。年次会議の基礎として、次の主要テーマが選択された。(1) IPCC と政策の影響に関する戦略の策定、(2) 需要シナリオの強化とモデルの補完性の推進、(3) ウェルビーイングを重視し、証拠ベースの研究の改善。

この会議では、いくつかの重要な全体会議キックオフが行われたほか、深い議論、対話、つながりのための多くの機会が提供された。同時に、セクターに重点を置いた分科会やサイドイベントにより、成果と影響を迅速に達成するための取り組みが促進された。会議は、主に対面形式で行われたが、オンラインでも参加者を迎えた。 会議は、モデル補完演習などの進行中の長期タスクを推進する必要があった。このタスクでは、エネルギー需要を大幅に削減するシナリオを開発、収集し、気候、経済、ウェルビーイングなどへの影響を評価した。並行して、EDITS は、選択された主要トピックをファーストトラック（FT）にて迅速に進めた。

年次総会は、3 つの優先テーマが特定され、これらは、WG、FT チームワーク内のあらゆる活動と研究の方向性の基盤となった。(括弧内は、EDITS 内の対応グループを示す。)

優先事項 1. モデリングの進展

- (需要) ソリューション空間の体系的な探索のためのフレームワークの改善 (FT)
- セクターモデル (SM) と IAM モデルの接続 (WG + メンバー)
- シナリオ データの収集、変換の改善、シナリオ コンパスの開発 (WG + メンバー)

優先事項 2. 政策の関連性の強化

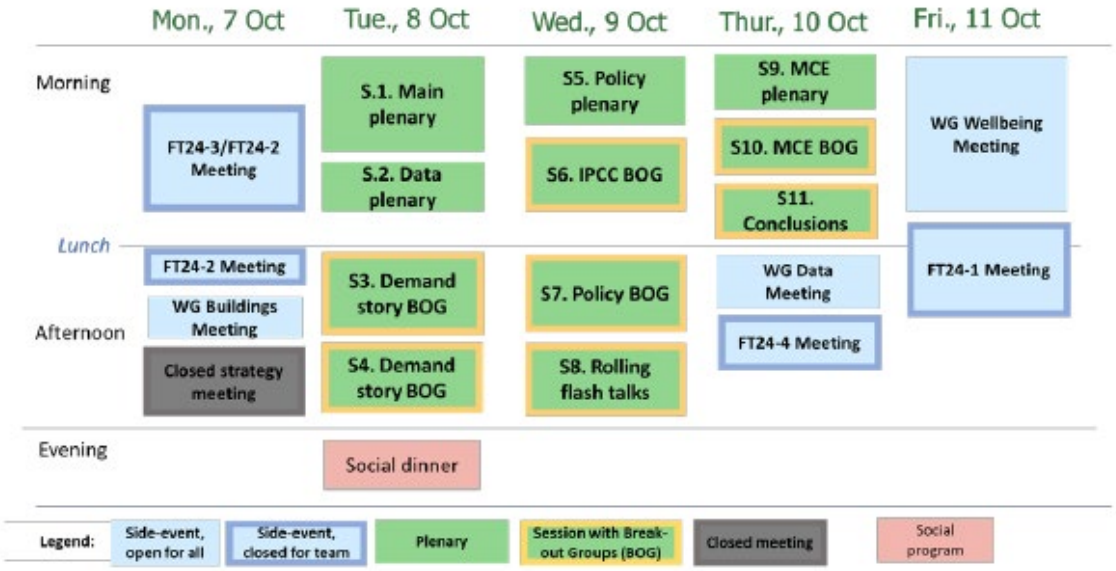
- 気候以外の需要側政策のパフォーマンスを評価する: 幸福、不平等、正義、雇用 (FT/メンバー)
- 需要側ソリューションを妨げる政策を調査する (FT/メンバー)
- 需要政策評価の方法論を開発して適用する (FT/メンバー)、次の点に重点を置く:
    - o 野心レベル、ベンチマーク、正義
    - o 政府と企業
- 非対称で動的であることを考慮して、受容性と実現可能性の評価を実施する (WG/FT/メンバー)

優先事項 3. ウェルビーイングの再構築

- より包括的な幸福の指標を開発し、それを使用してシナリオを評価する (FT)
- 方法論の開発とデータ収集を通じて、サービス提供の品質と不平等/アクセスを含める (WG/FT/メンバー)
- 消費回廊、下限、上限を適応させる。需要側に関連する定義、定量化、概念化に焦点を当てる (WG)

会議内容

5 日間の開催のうち、3 日は主要会議で、2 日は、サイドイベントで構成された。
主要な会議内容は以下の通り。（なおサイドイベントに関しては、セッション 11 の後に続く。）



開会（10/8）

セッション1

年次会議は、共同主催者である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った後、地球環境産業技術研究機構 (RITE)の秋元圭吾氏が日本のGX戦略と需要側の役割について、経済産業省の木村範尋氏がIPCC AR6およびAR7における需要側の証拠ベースについてスピーチを行った。またIPCCのWGIIIの副議長であるSiir Kilkis氏がIPCC AR7を踏まえたスコープと戦略についての全体会議で議論を行い開会した。

セッション 2: ワーキング グループのデータ

- WG データコア製品の紹介 (メタデータベース、指標ダッシュボード、コストと利点のデータ収集、データ ギャップの特定など)
- すでに利用可能な製品の進歩と使用、および次のステップに関する議論

セッション 3: ウェルビーイングと充足感に関する分科会
ブレークアウトグループ(BOG)では、トピックに関するキックオフ プレゼンテーションがいくつか行われ、その後、これらが互いにどのように関連しているか、また EDITS 内の他の研究や活動とどのように関連しているかについてグループ ディスカッションが行われた。

分科会 1
プレゼンテーション
- ✓ 生活の質に対する認識された影響は、人々の気候政策の好みをよりよく理解するのに役立つか?
- ✓ グローバルサウスにおける低需要と高いウェルビーイング: LED によるエネルギー節約以上のもの
- ✓ シナリオにおけるウェルビーイングと正義

プレゼンテーション後に、以下の議論を実施した。
(a) 政策の影響の認識、表明された好ましい不平等、公平性/正義の関係
(b) 関連セグメントごとのエネルギー使用量とギャップ、およびウェルビーイングへの影響
(c) DLS、ウェルビーイング、正義、および国/準国の気候コミットメントについて関係者を効果的に関与させる方法

分科会 2
プレゼンテーション
- ✓ 世界の各地域における充足度
- ✓ より広範な需要サイドの進化を表現するための新しいモデリングフレームワークー充足度やその他の可能性
- ✓ スイス国民の日常的なエネルギー使用の不平等に対する短期的な自給自足戦略
- ✓ 中国の建築業界におけるエネルギーの充足度、そして幸福と平等性を考慮した充足度対策

プレゼンテーション後に、以下の議論を実施した。
グローバル北部とグローバル南部における充足アプローチ

セッション 4:

分科会 1: セクター間の需要：材料

プレゼンテーション

- ✓ CircoMod プロジェクトにおける気候変動緩和のための循環型経済モデリング
- ✓ 循環型経済戦略による温室効果ガス排出量ネットゼロ達成への貢献：CircEUlar プロジェクトの活動
- ✓ 世界の建築資材とエネルギーの需要低下シナリオの影響

プレゼンテーション後に、需要側の特定の領域に焦点を当て、グループディスカッションを行った。

分科会 2: 需要のストーリーを伝える

需要側を幅広い聴衆にどのように位置付け、提示するかについてのグループディスカッションを実施した。LED/HwL の未来の中核要素として私たちが考えるもの、これらがさまざまな地域で何を意味するのか、あるいは普遍的なものなのかについて、理想的には、EDITS ネットワークを超えてより幅広いアイデアの収集が目的。EDITS ネットワークからのコンセンサスを目標とした。

分科会 3

LED に関する企業 (および政策) の取り組みに研究がどのように貢献できるかについてのグループディスカッション。

- ✓ ビジネスソリューションの役割: 材料とエネルギー効率に関する企業の取り組み
- ✓ 社会イノベーションの普及
- ✓ 日本のエネルギースタートアップ投資家から見た気候技術イノベーションファイナンス
- ✓ AI のエネルギー使用を管理するデータセンター運営者とテクノロジー企業の役割

セッション 5: ハイ・ウィズ・ロー政策 [全体会議]

このセッションでは、EDITS の取り組みを、政策や行動研究における同様の概念と結び付けた。

プレゼンテーション

- ➢ 新しいヨーロッパのバウハウス イニシアチブ
- ➢ 低エネルギー ライフスタイルとその政策実施

全般的な議論:

- ✓ LED 変革を促進する政策 (既存または将来) は何か
- ✓ 政策立案において EDITS が連携すべき相手は誰か
- ✓ 需要側研究から得られる、関連する政策を成功させるための重要なメッセージは何か

セッション 6: IPCC の影響に関する分科会

内容や形式など、IPCC AR7 および特別報告書への EDITS の主要なエントリポイントの特定を行った。

セッション 7: 政策分科会

需要側の実践的側面と政策的側面に密接に関連する特定の領域に焦点を当て、グループディスカッションを行った。

分科会 1

IPCC の都市に関する報告書に関連して、都市環境と都市についてのグループディスカッション

分科会 2

セクター間の需要：適切な生活水準

- ✓ 180 万の個別居住地の建築資材在庫に対する世界の需要: 南北格差と知識格差
- ✓ コロンビアのネットゼロ建築セクターへの道: 循環型経済の観点からの洞察
- ✓ 国連の SDG に間に合うように世界の適正な生活水準を達成するために必要な最小限の資材在庫の増加
- ✓ エネルギーと排出シナリオにおける適正な生活格差の解消
- ✓ スイスの DLS と不平等

プレゼンテーション後ディスカッションと一日を通して IPCC への影響に関する戦略に重点を置いた BOG から報告で締めくくった。

セッション 8: コミュニティの研究発表：ローリングフラッシュトーク

EDITS の活動は、メンバーのコア研究活動と密接に結びついている。EDITS の価値は、ネットワークの力と日々の進行中の研究を組み合わせ、共有された成果、新しい概念、斬新なアイデア、再定式化された方法を生み出すことにある。このセッションでは、EDITS 内外で進行中の関連する研究に関するフラッシュトークを開催した。

セッションは 40 分間の 2 つのパートに分かれており、3 つの並行した部屋でそれぞれ 3〜4 人のプレゼンターが参加した。プレゼンターはそれぞれ異なる聴衆に対して 2 回プレゼンテーションを行った。つまり、各参加者は選択したトピックのうち 2 つに参加した。

- ➢ 非技術的なイノベーション
  - ✓ 構造変化における緊張とトレードオフを乗り越えて幸福と持続可能性の移行を目指す
  - ✓ 日常生活のデジタル化
  - ✓ エネルギー需要の低い未来を切り開く社会イノベーションの推進者
  - ✓ 気候緩和提案の需要を集計するモデルとインタラクティブな計算機

- ➢ HwL の将来における仲介セクターとしてのモビリティと輸送

- ✓ 適切なモビリティとは何か、異質性への対処方法
- ✓ EDITS に関連する最新の PASTA 結果
- ✓ 在宅勤務が自動車燃料を含む家庭のエネルギー需要に与える影響: 日本の公式統計を使用した分析
- ✓ シェアードモビリティが車両群の入れ替えに与える影響-スウェーデンの統計に基づく半経験的モデル

- ➢ 産業と排出削減が困難なもの
  - ✓ 削減困難なセクターとマイナスの排出
  - ✓ 中国における産業の脱炭素化
  - ✓ 中国のアンモニアエネルギーのカーボンフットプリントと経済分析
  - ✓ 低エネルギー需要シナリオの分析：気候変動影響評価による CGE とインデックス分解

セッション 9: モデル補完性演習 [全体会議]
プロトコル WG は、2023 年から 2024 年にかけて、新しいシナリオの開発を可能にし、補完性の取り組みを具体化するために非常に活発に活動してきた。MCE はモビリティに重点を置いており、段階的に他のセクターにも拡大される。このセッションでは、これまでの進捗状況と教訓について議論し、今後の計画についても検討した。

プレゼンテーション
- ➢ EDITS での LED シナリオ開発の枠組み
- ➢ LED/HwL シナリオファミリーの拡張: モビリティの事例
- ➢ LED と HwL の本当の意味を思い出す
- ➢ インドにおける LED とは: インド DLE FT からの教訓

全体会議で以下の議論を行った。
- ✓ LED を細分化する方法 - 例: セクター、社会気候経済政策目標、技術革新、対社会革新。エネルギー削減が常に実現されるわけではない。
- ✓ LED のモビリティセクターの主な推進要因は何か (現在および将来含まれるものを考慮して)
- ✓ MCE がどのように、またなぜ機能するか (異なるモデルのリンク、データ フロー (出力->入力)、比較など)

セッション 10: シナリオ分科会
これらのブレークアウトグループ (BOG)は、シナリオと MCE の進め方に焦点を当てた。

<u>分科会 1</u>

- ✓ MCE 輸送モデル: メッセージ輸送、IIASA (オーストリア)
- ✓ MCE 輸送モデル: DNE21+、RITE (日本)
- ✓ MCE 輸送モデル: PASTA、OECD-ITF (フランス)
- ✓ ラストマイル輸送の技術的および経済的モデリング: ブラジルの事例、COPPE (ブラジル)
- ✓ 輸送需要シェアの想定が上流エネルギーシステムの結果に与える影響、IIASA (オーストリア)

分科会 2

- ✓ 交通、建物、産業に関する ECEMF プロジェクトによる需要側モデルの比較の概要、TUW (オーストリア)
- ✓ スプロール現象のシナリオ、EPFL (スイス)
- ✓ PIER を使用したインドのボトムアップ エネルギー需要推定、Prayas (インド)
- ✓ TREES を使用した DLS-ハイテクシナリオ、大阪大学 (日本)

閉会 (10/10)

セッション 11:

IIASA の Benigna Boza-Kiss 氏と Bas van Ruijven 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。

サイドイベント

10/7: FT のセクター横断の議論、社会変革に議論の後、2025 年に展開される EDITS 内の建物と家庭の電気製品に関するモデル補完性演習(MCE)の実行に関して議論した。
また、午後から EDITS 戦略ミーティングを招待されたメンバー、WG リーダーのみで行われた。
10/10: セッション 11 の後、データ WG、FT のコストとベネフィットデータと適切なモビリティに関して会議を実施。
10/11: ウェルビーイング WG の会議が開催された。

付表 1 国際ワークショップの参加者リスト

	国	組織名	参加者名	IPCC 関係者
1	Japan	Ministry of Economy, Trade, and Industry (METI)	Norihiro Kimura	
2		Research Institute of Innovative Technology for the Earth (RITE)	Keigo Akimoto	Ch.17 LA
3			Takahiro Nagata	
4			Miyuki Nagashima	

	国	組織名	参加者名	IPCC 関係者
5			Fuminori Sano (Online)	
6			Ayami Hayashi	
7			Yuko Nakano	
8			Naoko Onishi (Online)	
9			Jubair Sieed	
10			Atsuko Fushimi	
11		University of Tokyo, Institute for Future Initiatives (UTokyo IFI)	Masahiro Sugiyama	Ch.12 LA
12			Tao Cao	
13			Hiroyoshi Iwata	
14		Osaka University; Urban Energy System Lab.	Yoshiyuki Shimoda	
15			Yohei Yamaguchi	
16		The Institute of Energy Economics, Japan (IEEJ)	Yi-chun Chen	
17	Indonesia	IPB University	Joni Jupestra	Ch.17 LA
18	Thailand	Asian Institute of Technology (AIT)	Joyashree Roy	Ch.5 CLA, Synthesis Core writing
19			Joyee Chatterjee	
20			Ninaad Desai	
21			Firuz Ahamed Nahid	
22			Sirayuth Thongprasert	
23	India	Center for Study of Science, Technology and Policy (CSTEP)	Kaveri Ashok	
24		Prayas (PEG)	Ashok Sreenivas	
25	South Korea	Yonsei University/Korea International Economic Association	Tae Yong Jung	Ch.15 CLA
26			Yong-Gun Kim	Ch.2 LA
27			Jongwoo Moon	
28	China	Tsinghua University	Xunmin Ou	Ch.10 LA
29			Shan Hu	
30	Austria	International Institute for Applied Systems Analysis (IIASA)	Arnulf Grübler	Ch.5 LA
31			Keywan Riahi	Ch.3 CLA
32			Bas van Ruijven	
33			Benigna Boza-Kiss	
34			Paul Kishimoto	

	国	組織名	参加者名	IPCC 関係者
35			Alessio Mastrucci	
36			Leila Niamir	
37			Shonali Pachauri	Ch.2 LA
38			Caroline Zimm	
39			Elina Brutschin	
40			Aneeque Javaid	
41			Florian Maczek	
42			Jihoon Min	
43			Yiyi Ju	
44			Jarmo Kikstra	
45			Volker Krey	Ch.4 LA
46			Karl Scheifinger	
47			Gamze Ünlü	
48			Pat Wagner	
49			Lydia Gericke	
50		Toyota Motor Company/IIASA	Takuya Hara	
51		University of Natural Resources and Life Sciences, Vienna (BOKU/SEC)	Dominik Wiedenhofer	
52			Jan Streeck	
53			Andre Baumgart	
54		TU Wien	Lukas Kranzl	
55		Central European University (CEU), IPCC	Diana Urge-Vorsatz	IPCC ViceChair, Ch.8 RE
56	France	International Transport Forum (ITF/OECD)	Luis Martinez	
57			John Pelayo Pritchard	
58		Réseau de Transport d'Electricité (RTE)	Bianka Shoai-Tehrani	
59		European Securities and Markets Authority (ESMA)	James Glynn (Online)	
60	UK	University of Oxford	Charlie Wilson	
61			Poornima Kumar	
62		University of Plymouth	Souran Chatterjee	
63		University of Leeds	Joel Millward-Hopkins	
64		University of Cambridge	Jennifer Hawkin	
65	Italy	Euro Mediterranean Center on Climate Change (CMCC)	Massimo Tavoni (Online)	Ch. 3 LA
66			Elena Verdolini	Ch.16 LA

	国	組織名	参加者名	IPCC 関係者
67			Enrico Cofler	
68	Germany	Reiner Lemoine Institute (RLI), Berlin	Marlin Arnz	
69			Zakia Soomauroo	
70		University of Freiburg	Stefan Pauliuk	
71			Johan Vélez Henao	
72			Frauke Wiese (Online)	
73		Oeko-Institut	Carina Zell-Ziegler (Online)	
74		Mercator Research Institute on Global Commons And Climate Change (MCC)	Felix Creutzig (Online)	Ch.5 CLA
75		Agora Energiewende	Simon De Stercke	
76		Leuphana University Lüneburg (SESI)	Maria Fernanda Godoy Leon	
77			Ernest Aigner	
78		Forschungsinstitut für Nachhaltigkeit - Helmholtz-Zentrum Potsdam (RIFS Potsdam)	Kreinin Halliki	
79	Belgium	Ghent University	Gwenny Thomassen	
80	Portugal	University Institute of Lisbon (ISCTE-IUL)	Nuno Bento	
81	Netherlands	Universiteit Utrecht (UU)	Oreane Edelenbosch	
82		University of Groningen	Linda Steg	Ch.6 LA
83			Anne van Valkengoed	
84		Leiden University (CML)	Tomer Fishman	
85	Switzerland	EPFL Laboratory of Environmental and Urban Economics (EPFL)	Sascha Nick	
86		University of Lausanne	Vivien Fisch-Romito	
87	Sweden	Chalmers University of Technology	Maximilian Forberg	
88			Johannes Morfeldt	
89	USA		Nan Zhou	Ch.4 LA

	国	組織名	参加者名	IPCC 関係者
90		Lawrence Berkeley National Laboratory (LBNL)	Jingjing Zhang	
91		University of California, Santa Barbara (UCSB)	Eric Masanet	Ch.5 LA
92		Oak Ridge National Laboratory (ORNL)	David McCollum	
93		Wisconsin Energy Institute/ University of Wisconsin	Gregory Nemet	Ch.2 LA
94		Rocky Mountain Institute (RMI)	Yuki Numata	
95	Brazil	Economia da Energia do Programa de Planejamento Energético da COPPE/UFRJ	Roberto Schaeffer	Ch.3 CLA
96	Turkey	The Scientific and Technological Research Council of Türkiye, IPCC	Siir Kilkis	WGIII ViceChair, Ch.8 LA

※ IPCC 関係者は、第 6 次評価報告書の執筆者

各研究機関報告書一覧

	タイトル	研究所・大学
①	低エネルギー需要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. Energy sufficiency for deep decarbonization: A modeling framework	Lawrence Berkeley National Laboratory (LBNL)
	2. Progress Report for FY24: Demand-Side Databases Description	
③	1. Small Increases in Socioeconomic Material Stocks Can Secure Decent Living Standards Globally [*Abstract only]	University of Natural Resources and Life Sciences, Vienna; Universität für Bodenkultur Wien (BOKU)
	2. Can the circular economy save the climate? A review of the national to global evidence [*Abstract only]	
④	More benefits with lower demand- Quantifying the co-benefits of energy demand measures in the Residential building sector [*Abstract only]	University of Plymouth
⑤	Carbon emissions and cost analysis of the entire hydrogen supply chain for steel industry in China [*Public version]	Tsinghua University
⑥	Demand-side Energy Efficiency in Brazil: Evaluating Heatwave Impacts on Daily Electricity Demand in the Interconnected Power System [*Abstract only]	Universidade Federal Do Rio De Janeiro / Technological Management Center of COPPE (UFRJ/COPPETEC)
⑦	Analyzing Low Energy Demand Scenarios: LEDS potential for reducing dependence on CCS and the impacts of production-based and consumption-based carbon pricing in LEDS	Korea International Economic Association (KIEA)
⑧	Quantifying minimum mobility needs: the Who, the Where and the Why [*Abstract only]	Reiner Lemoine Institute gGmbH (RLI)
⑨	Demand-side mitigation solutions: analyzing the current state of data, opportunities, and paths ahead [*Abstract only]	Utrecht University (UU)
⑩	Decarbonizing the Building Sector: The Role of Efficiency, Sufficiency, and Behavioural Measures [*Abstract only]	DBH InnoHub/Central European University (CEU)
⑪	1. Method, Data and Estimation of Cross sectoral mitigation potential of demand side solutions with special reference to South and South East Asia	Asian Institute of Technology (AIT)
	2. Improving community resilience through distributed solar energy as critical infrastructure – a case study of South Asia	
	3. Demand-side climate change mitigation: where do we stand and where do we go?	
⑫	1. Energy requirements for securing wellbeing in Switzerland and the space for affluence and inequality [*Abstract only]	EPFL
	2. Systems perspectives on transforming Swiss housing by 2040: wellbeing, shared spaces, sufficiency,and de-sprawl	
⑬	Model complementarity exercise on demand-side innovations for climate change mitigation [*Public version]	東京大学 未来ビジョン研究センター

	タイトル	研究所・大学
⑭	1. Integrating Transport Demand and Fleet Modelling: Regional Dynamics in Decarbonization Pathways [*Abstract only]	ITF-OECD
	2. Evidence is clear: Mitigating Climate Change through demand side solutions puts less burden on the society [*Abstract only]	
⑮	Inertia in consumer's choice of a suitable contract and consumption patterns in the electricity market [*Abstract only]	Euro-Mediterranean Centre for Climate Change (CMCC)
⑯	Distributional Impacts of Demand-side Technological Innovations in three Advanced Economies [*Abstract only]	Oxford University
⑰	New Advances in Energy Demand Research: Novel Methodology for Estimating Structural Change Effects [*Abstract only]	Iscte – University Institute of Lisbon
⑱	Large Dispersion in the Diffusion of Social Innovations	University of Wisconsin (WISC)
⑲	Well with low: How do people expect sustainable lifestyles will affect their wellbeing? [*Abstract only]	University of Groningen (RUG)
⑳	Energy and Water Use of Data Centers: A Comprehensive Review [*Abstract only]	University of California, Santa Barbara (UCSB)
㉑	Annual Report - Energy Demand changes Induced by Technological and Social innovations (EDITS)	International Institute for Applied Systems Analysis (IIASA)
㉒	2024 年度 EDITS プロジェクト報告書 都市エネルギーシステム領域 [*Public version]	大阪大学 大学院工学研究科

*ジャーナル掲載前の論文のため、全非公開の場合は、abstractのみ公開、部分的に非公開箇所がある場合は、公開バージョンのみ公開

低エネルギー需要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 [1]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。

そして、日本政府は、2025 年 2 月に、地球温暖化対策計画の改定 [2]を行い、引き続き 1.5℃未満を目指すとした上で、2035 年および 40 年の NDC としての温室効果ガス排出削減目標を、それぞれ、2013 年度比で 60%削減、73%削減とすることとし、日本の NDC として UNFCCC 事務局に提出も行った [3]。これら目標は、既に提出済みの 2030 年 43%削減から 2050 年実質ゼロ排出（100%削減）に至る直線的な削減にあたるものである。既往の削減目標は維持し、気候変動への対応を進めながら、他方で、複雑化してきている国際情勢にも対応するパスが選定されたものと考えられる。第 7 次エネルギー基本計画 [4]、GX2040 ビジョン [5]も策定し、地球温暖化対策計画とともに閣議決定がなされたところである。

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[6)]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（次ページ以降に抜粋)。

また、2024 年 4 月にトリノで開催された気候・エネルギー・環境大臣会合[7)]でも、「我々は、全ての国、特に気温上昇を 1.5℃に抑えることを射程に入れ続けるために最も重要な排出軌道を有する主要経済国に対し、GST の成果に対応し、今世紀半ばまでのネット・ゼロに整合的で、全ての GHG、セクター及び分類を含む経済全体の総量削減目標を含み、利用可能な最良の科学に基づき、地球温暖化を 1.5℃に抑えることに整合した NDC を 2025 年初頭までに通報するよう求める。」とされ、

- 我々は、2030 年までにエネルギー効率改善率を世界平均で 2 倍となる 4 %にするという COP28 での UAE コンセンサスにおけるコミットメントを確認し、全ての国に対し、この目標達成に向けた追加的な取組をとるよう求める。省エネルギーは第一の燃料であり、エネルギー安全保障に資するクリーンエネルギー移行の不可欠な要素である。
- 我々は、効果的な省エネルギー対策及び投資促進の基礎として、国及び地方レベルでの適切な規制枠組みと、ヒートポンプ、デマンドサイドマネジメント、デジタル化などの既存及び革新的な技術に関する加速された行動の重要性を強調する。
- エネルギー効率 2 倍目標を支える、スマートで、都市型の、クリーンかつ持続可能なエネルギー移行を加速させる触媒としての都市の役割と、デジタル化がもたらす利点を認識している。

等とされた。

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。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。他方、需要側技術の普及における障壁を理解することは、その障壁除去のためにも重要である。IPCC 報告書におけるコストとポテンシャル推計に焦点を当てた分析を行った。これは査読論文としても採択された。

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）[8]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[9]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 10)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[11]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 1.2-1 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。

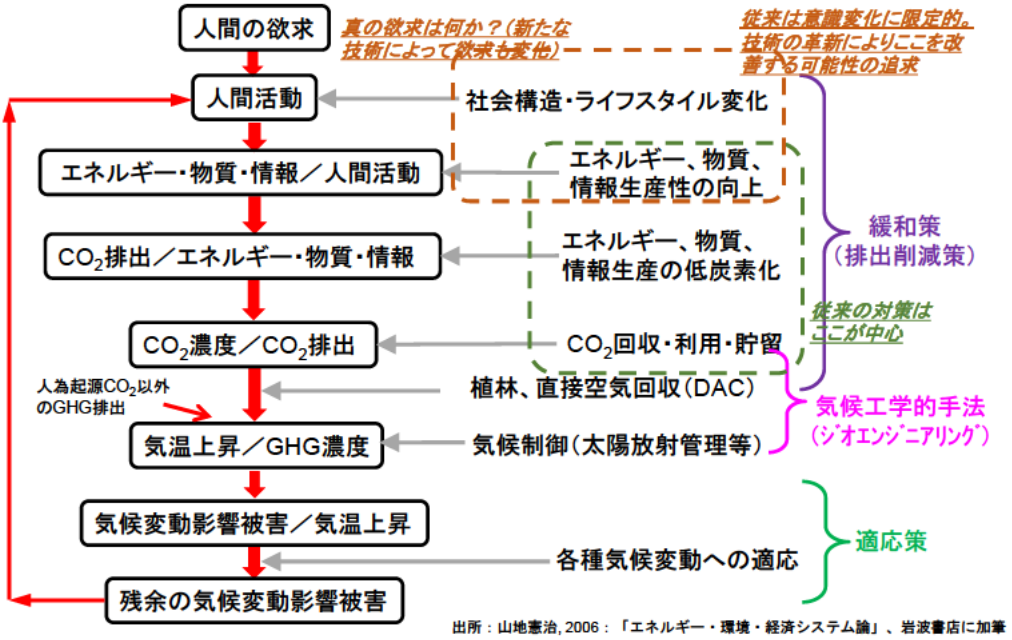


図 1.2-1 地球温暖化対策の基本構造と社会構造・ライフスタイル変化の位置づけ

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 12)など)。IPCC 第 6 次評価報告書（AR6）[11]でも、文献 12)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 1.2-2、図 1.2-3 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。

なお、GX2040 ビジョン [5]でも経済と環境の好循環において、AI による電力増はあるものも、AI を活用した、サーキュラー・シェアリングエコノミー等の誘発による排出削減効果についての指摘もなされたところである。

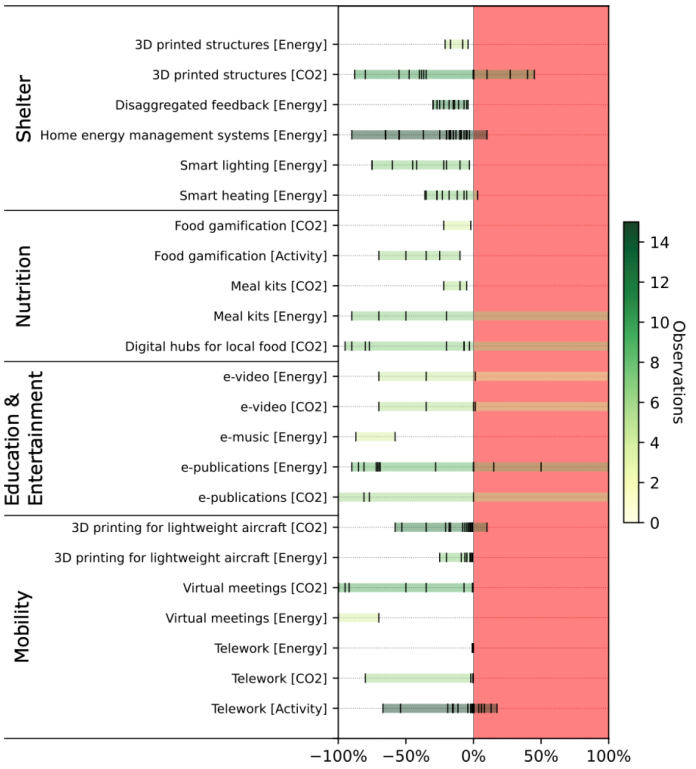


図 1.2-2 デジタル化によるエネルギー消費・CO_2 排出への影響

（出典：IPCC WG3 AR6[11]）

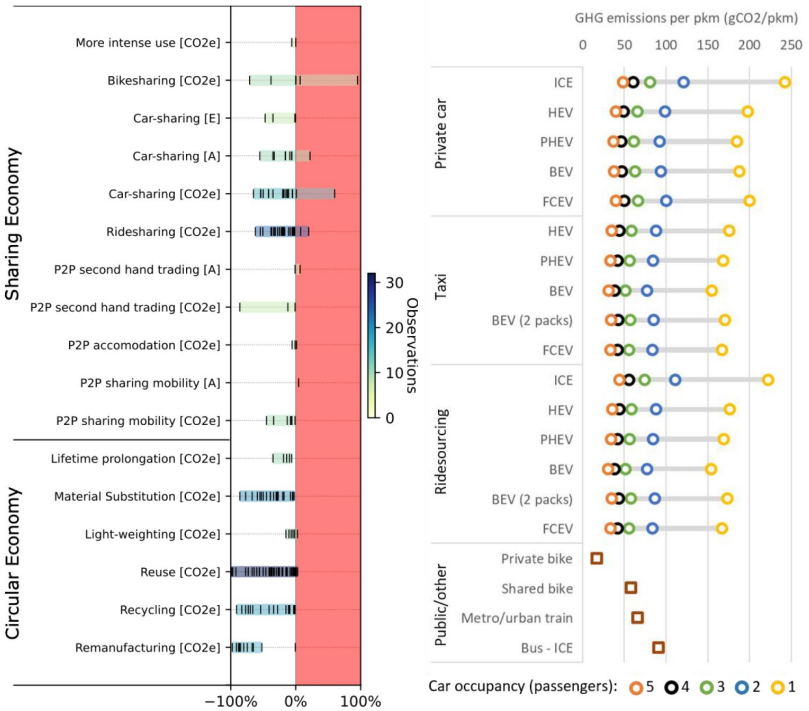
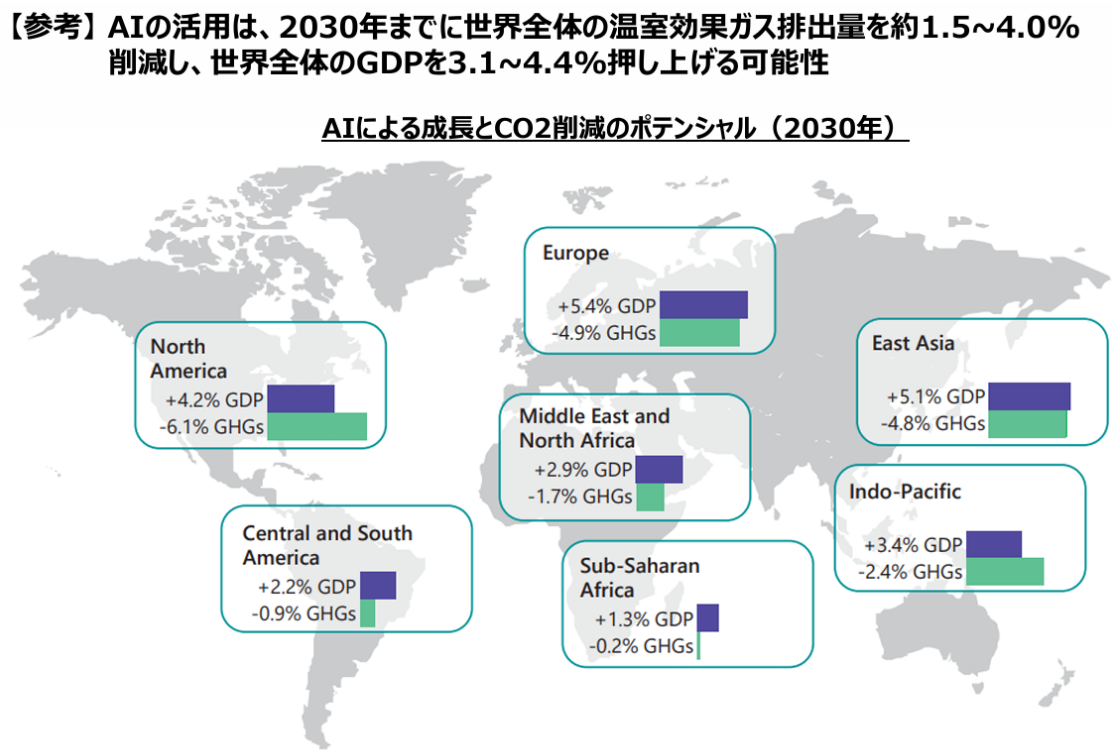


図 1.2-3 シェアリング・サーキュラーエコノミーによるエネルギー消費・CO_2 排出への影響

（出典：IPCC WG3 AR6[11]）



（出所） Microsoft,PwC（2019）“How AI can enable a sustainable future”

図 1.2-4 GX2040 で掲載された AI 活用による CO2 排出削減と GDP 増の推計例
（出典：GX2040 ビジョン [5]）

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 [12),13)]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 2.1-1 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 [15]。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 2.1-2 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。

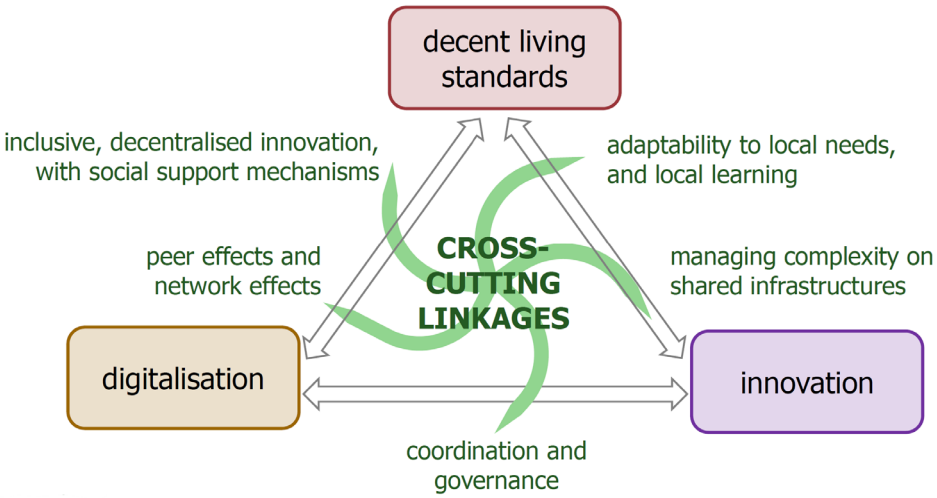


図 2.1-1　定性的シナリオ’High-with-Low’の想定ドライバー
（出典：EDITS WG3 Narratives group シナリオ [15]）

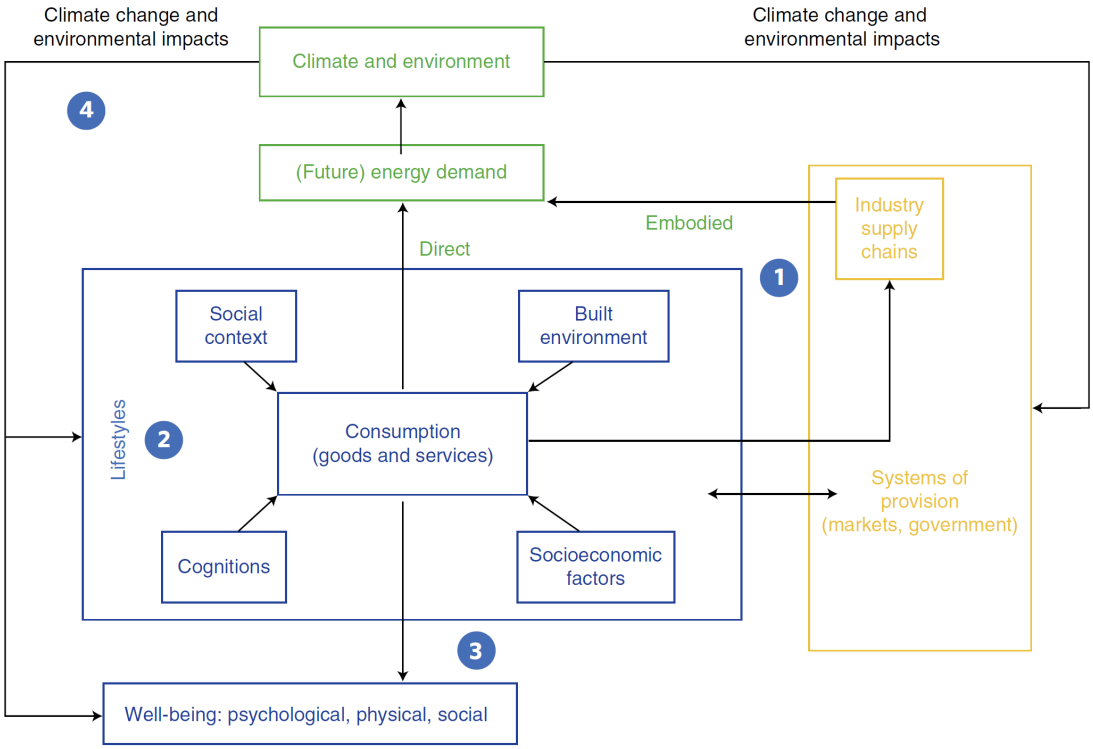


図 2.1-2 定性的シナリオ’High-with-Low’の要素間の関係

（出典：EDITS WG3 Narratives group シナリオ [15]）

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 2.1-1 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 2.2-1、表 2.2-2 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 2.2-3 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 2.2-1　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 2.2-2 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 2.2-3 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 2.2-1 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 2.2-2、風力発電コスト:図 2.2-3、EV の車両コスト:表 2.2-4、HP 給湯器のコスト:表 2.2-5、コジェネレーションシステムのコスト:表 2.2-6 として示している。

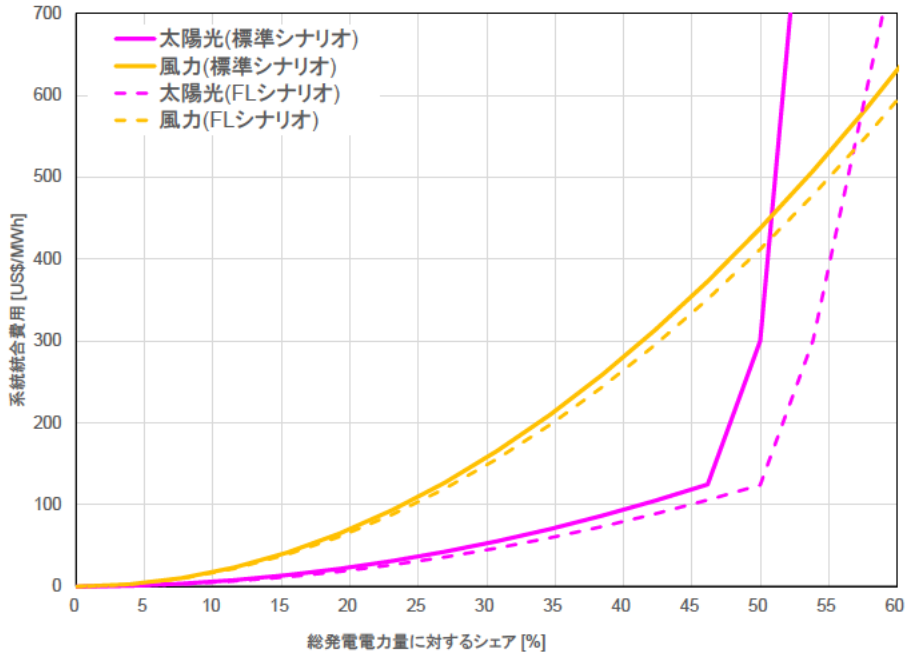


図 2.2-1 系統統合費用の想定（日本、2050 年、標準シナリオと FL シナリオ）

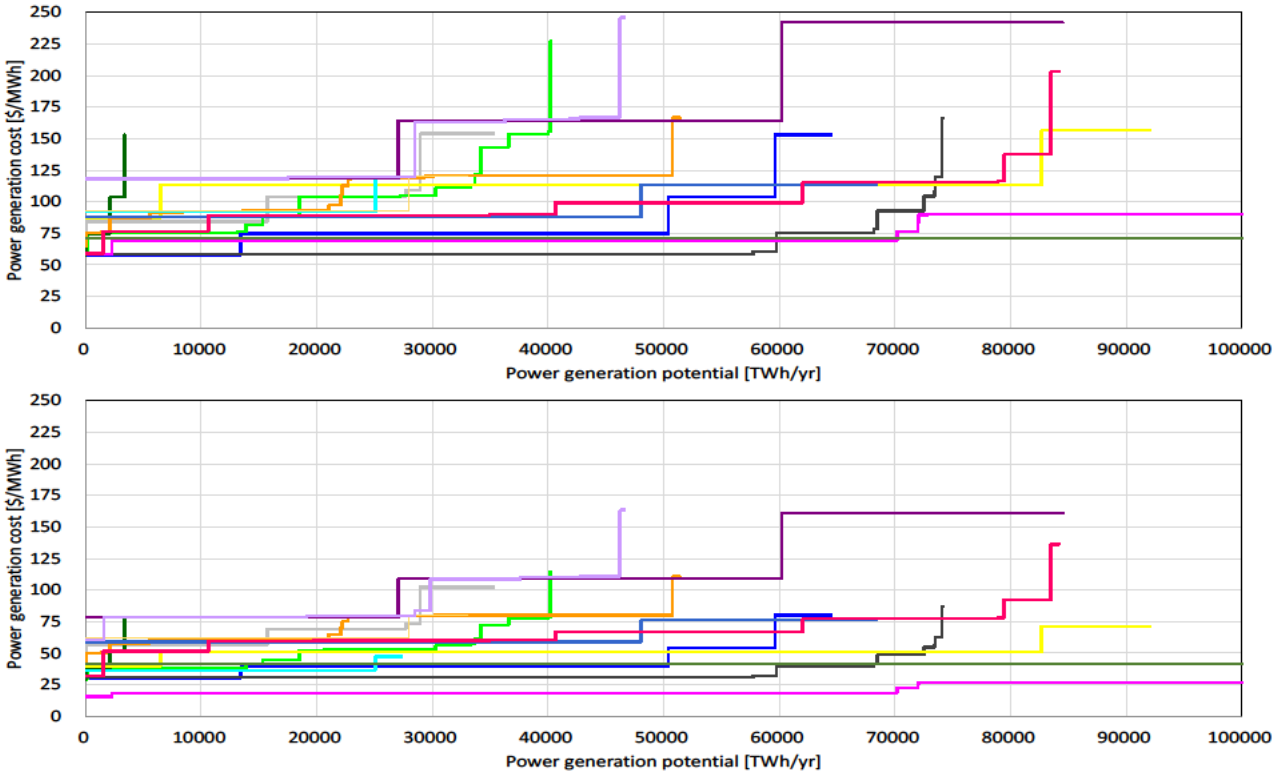


図 2.2-2 太陽光発電コストの想定（上図：標準、下図：GR シナリオ）

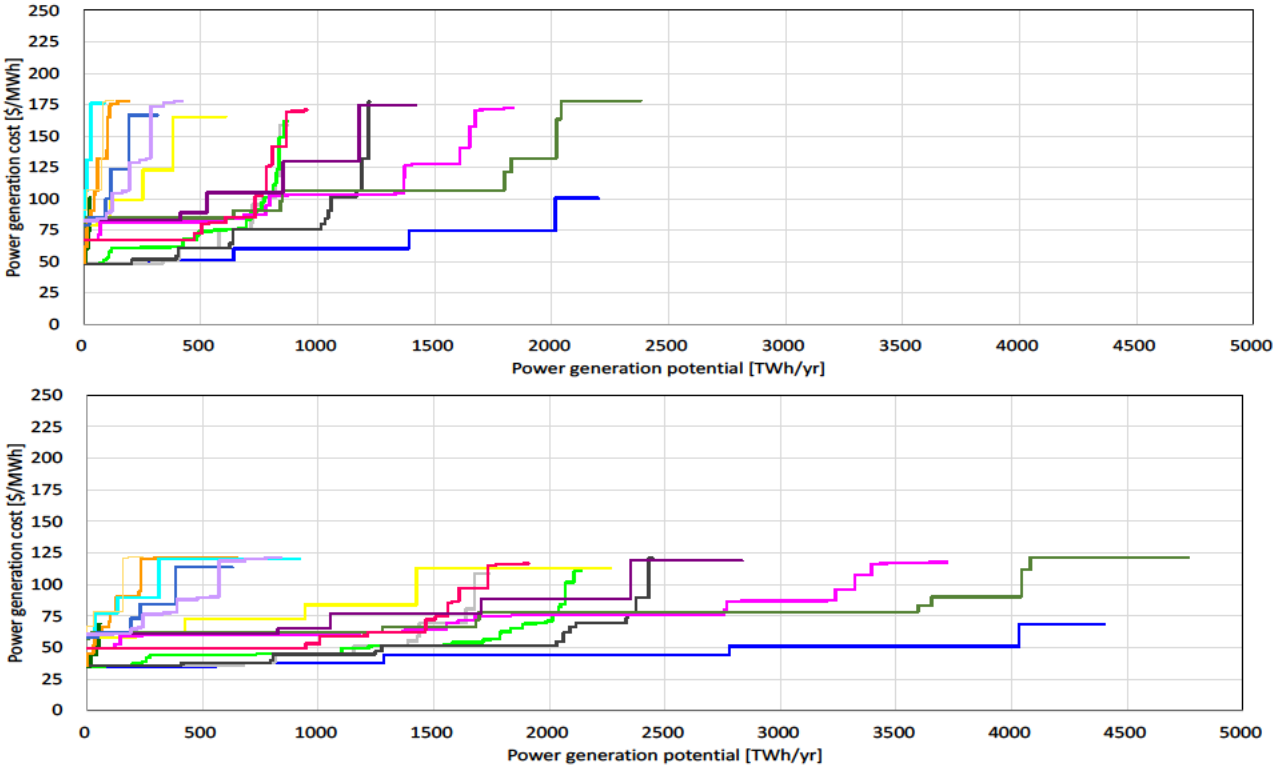


図 2.2-3 風力発電コストの想定（上図：標準、下図：GR シナリオ）

表 2.2-4 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 2.2-5　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 2.2-6　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 2.3-1 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 2.3-2 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 2.3-3 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。

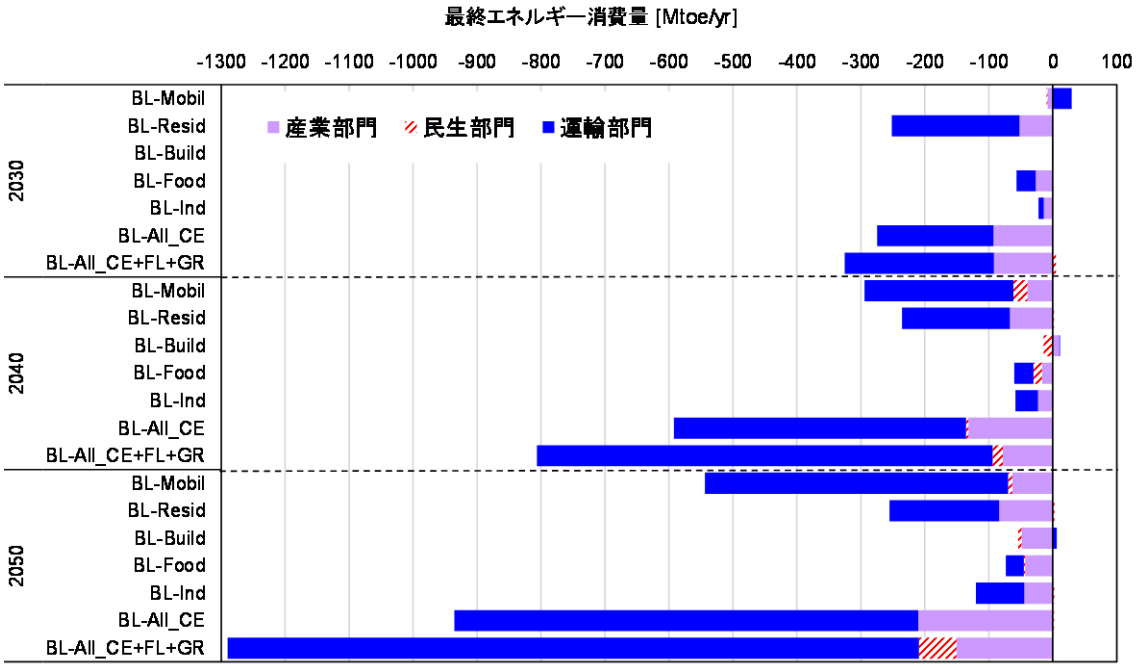
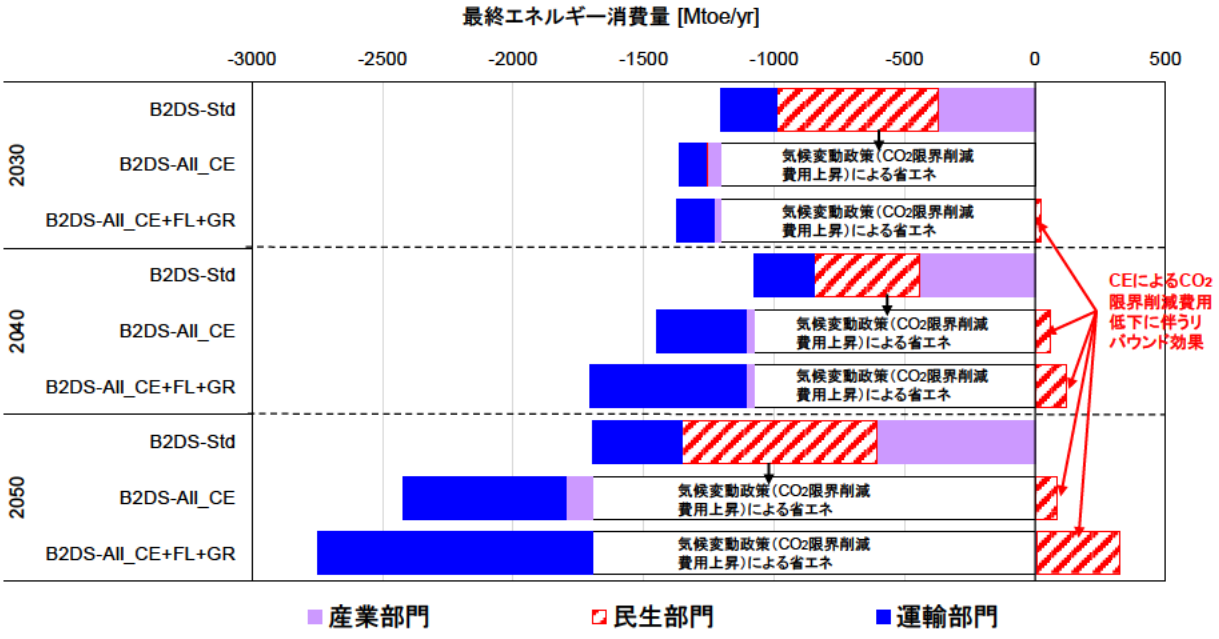
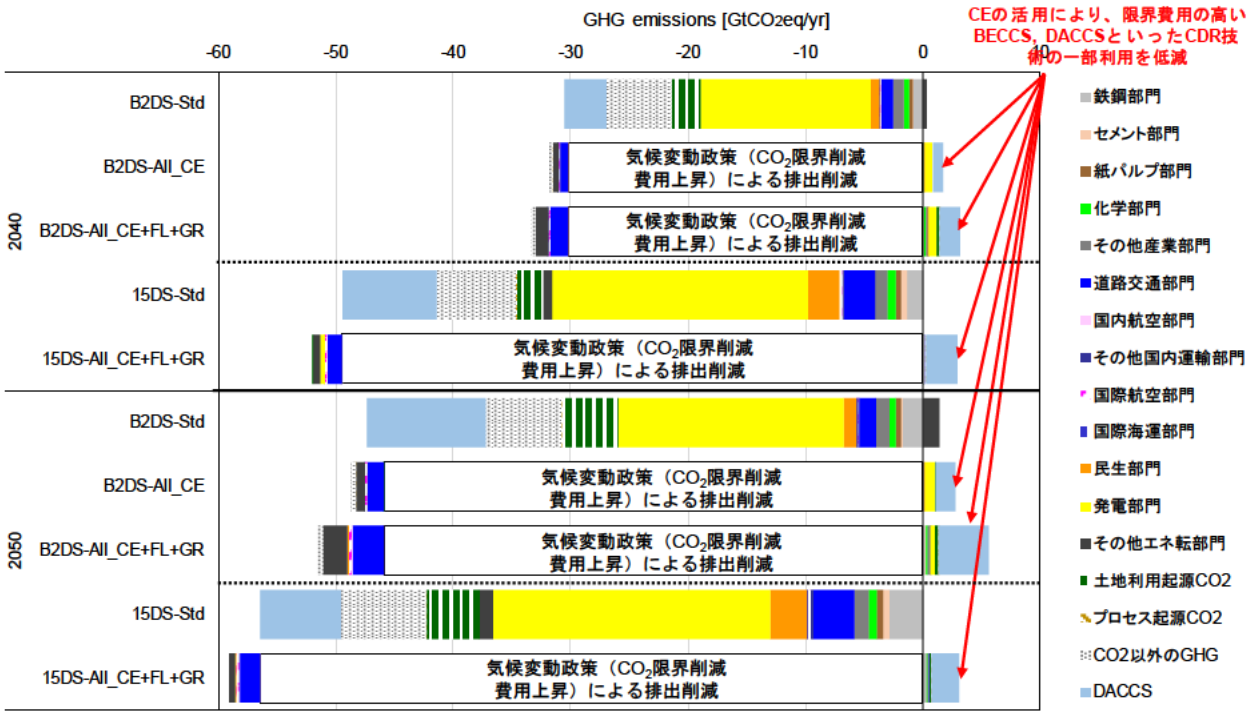


図 2.3-1 世界エネルギー消費量（ベースラインシナリオ、CE 想定時の変化）



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 2.3-2 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 2.3-3 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）

2.3.2 DX 等の需要対策によるコストへの影響試算

表 2.3-1 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。

表 2.3-1 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

第3章　運輸部門のシェアリング分析の国際モデル比較分析に向けた調整

3.1　分析の目的

運輸部門の LED シナリオ策定のため、OECD/ITF、IIASA 他と連携し、運輸部門のモデル比較・シナリオ比較を実施した。ここでは、デジタル化の進展に伴い全世界な導入・拡大が見込まれるシェアモビリティに着目した。シェアモビリティは、エネルギーや物質の需要低減、さらに wellbeing の向上に寄与すると期待される。

例えば RITE の DNE21+モデルを用いた既往の分析によると、自動運転ライドシェア、カーシェアを考慮したシナリオでは、カーボンニュートラル（CN）達成のための CO_2 限界削減コストや、鉄鋼、プラスチック、セメント等物質需要が低減する[16)]。図 3.1-1、図 3.1-2 は、それぞれ、文献 16)で示された、モデル想定の計算プロセスと道路交通部門の最終エネルギー消費量の推計例である。

より進展した分析にし、また、複数モデルによるシナリオ分析を実施し、ロバスト性と信頼性を有するシナリオ提示を行うため、OECD/ITF、IIASA 他と連携した分析を実施した。

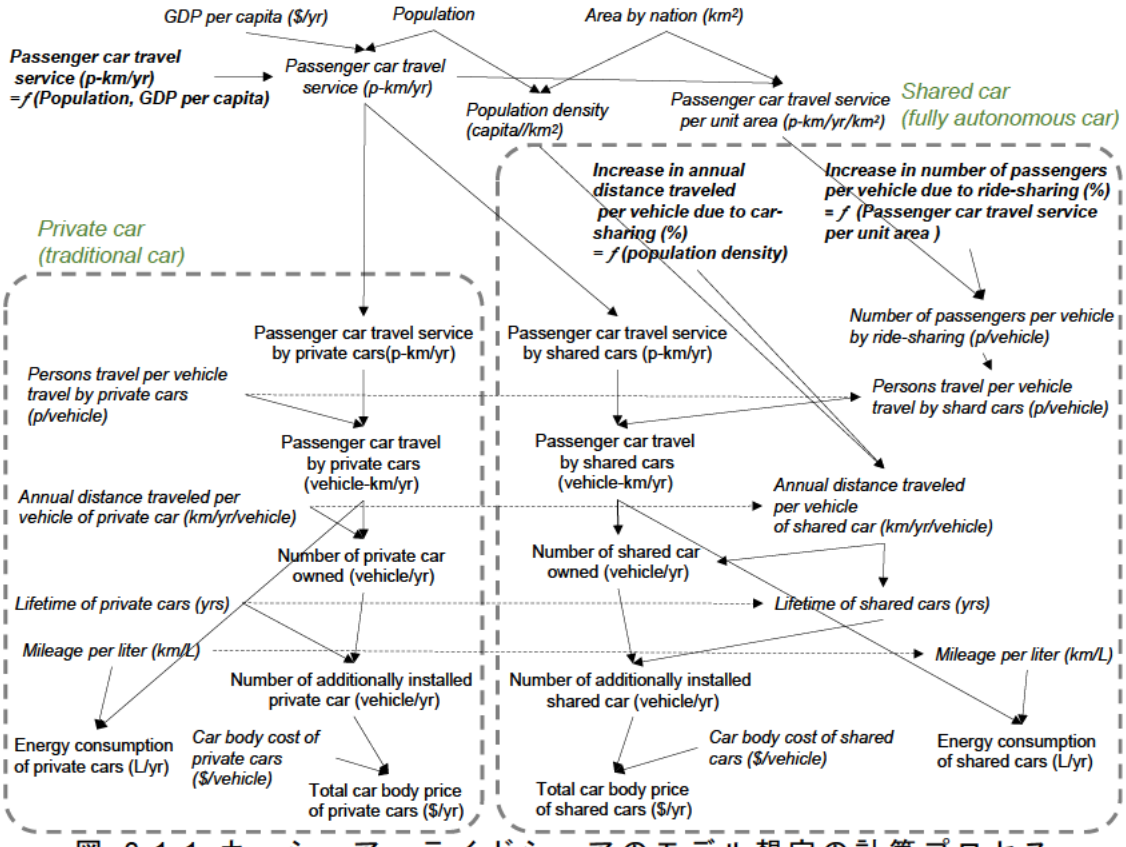


図 3.1-1 カーシェア・ライドシェアのモデル想定の計算プロセス

（出典：文献 16)）

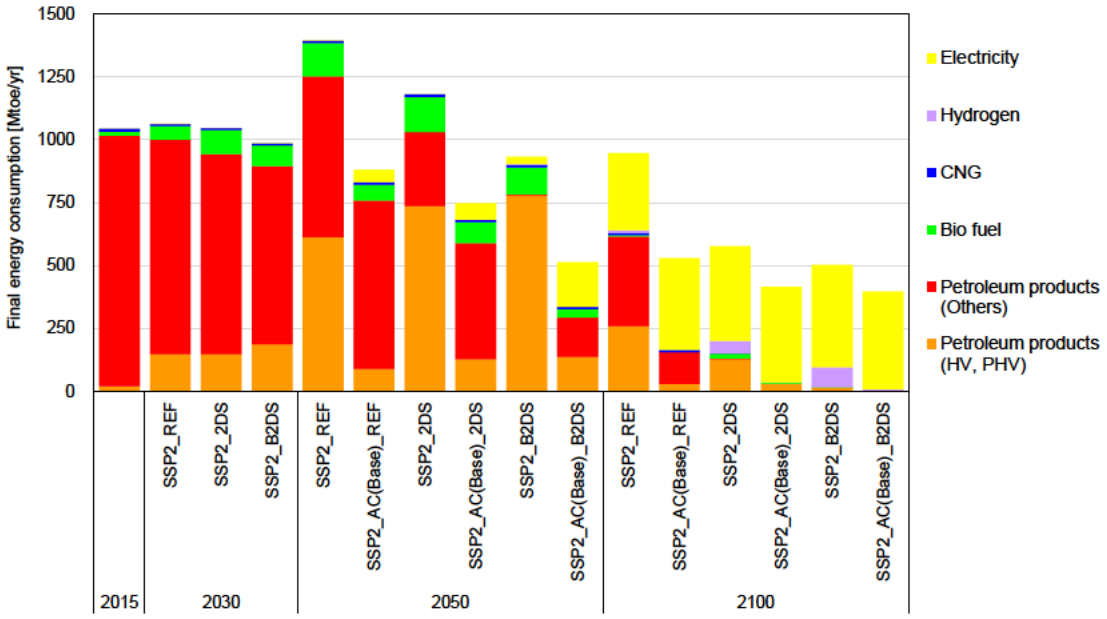


図 3.1-2 カーシェア・ライドシェアの道路交通部門での最終エネルギー消費量の評価例

（出典：文献 16)）

3.2 モデル比較評価に向けた分析

OECD/ITF の PASTA モデルは、運輸部門の政策目標と持続可能性評価を目的に開発されたもので、旅客と貨物をそれぞれ都市と非都市のサブモデルで表現する。このうち都市旅客モデルは世界 9200 以上の都市内の移動に関し 18 のモードを考慮し、カーシェア、ライドシェア、速度制限、公共交通サービスの向上等の交通政策シナリオに対し、CO_2 や大気汚染物質の排出量の低減、混雑度、アクセス度の改善等が算定されている。IIASA の MESSAGEix-Transport は、統合評価モデル MESSAGEix-GLOBIOM のサブモデルの一つで、旅客、貨物の需要、サービス・技術の詳細化が図られている。これらモデルには、得意とする要素の違いがあることから、モデル比較・シナリオ比較と同時に、モデル分析を互いに補完し合うことにより、シェアモビリティによる気候変動緩和への効果をより良く理解し、政策立案のためのより優れた情報提供を目的としている。

需要サイドの分析では、とりわけ国・地域別のシナリオとなると、そもそも各モデルが前提としている実績値のデータにも大きな差異が見られる。そこで今年度は、その差異の理解の促進、調整作業を実施した。図 3.2-1 は DNE21+モデルと PASTA モデルで人口シナリオを比較している。3 か国を見る限り将来の人口シナリオに大きな差は見られない。なお、GDP は、人口よりも差異は見られるものの、後述のサービス需要のような大きな差異はない（図 3.2-2)。

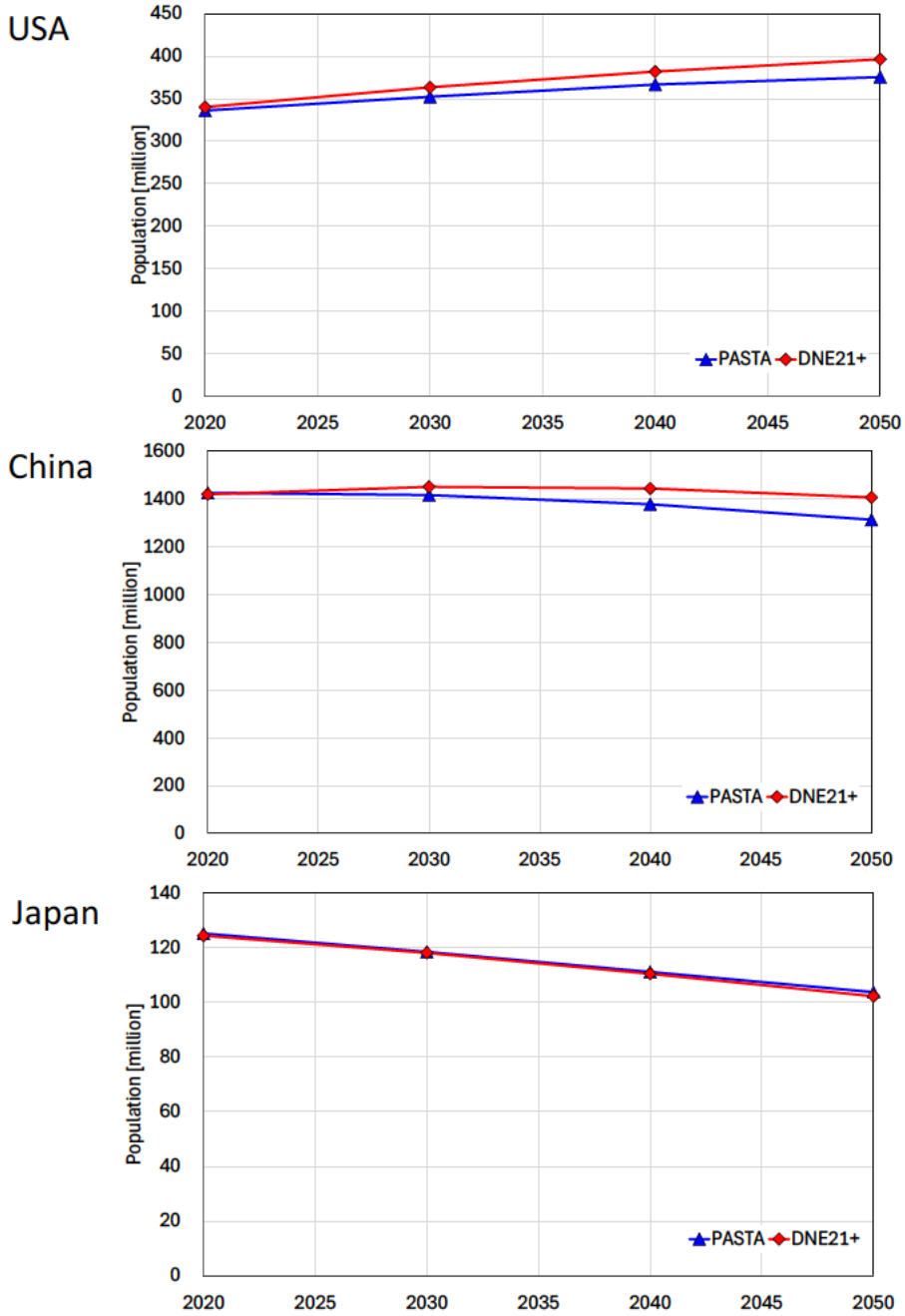


図 3.2-1 DNE21+と PASTA モデルでの人口シナリオ比較（米国、中国、日本）

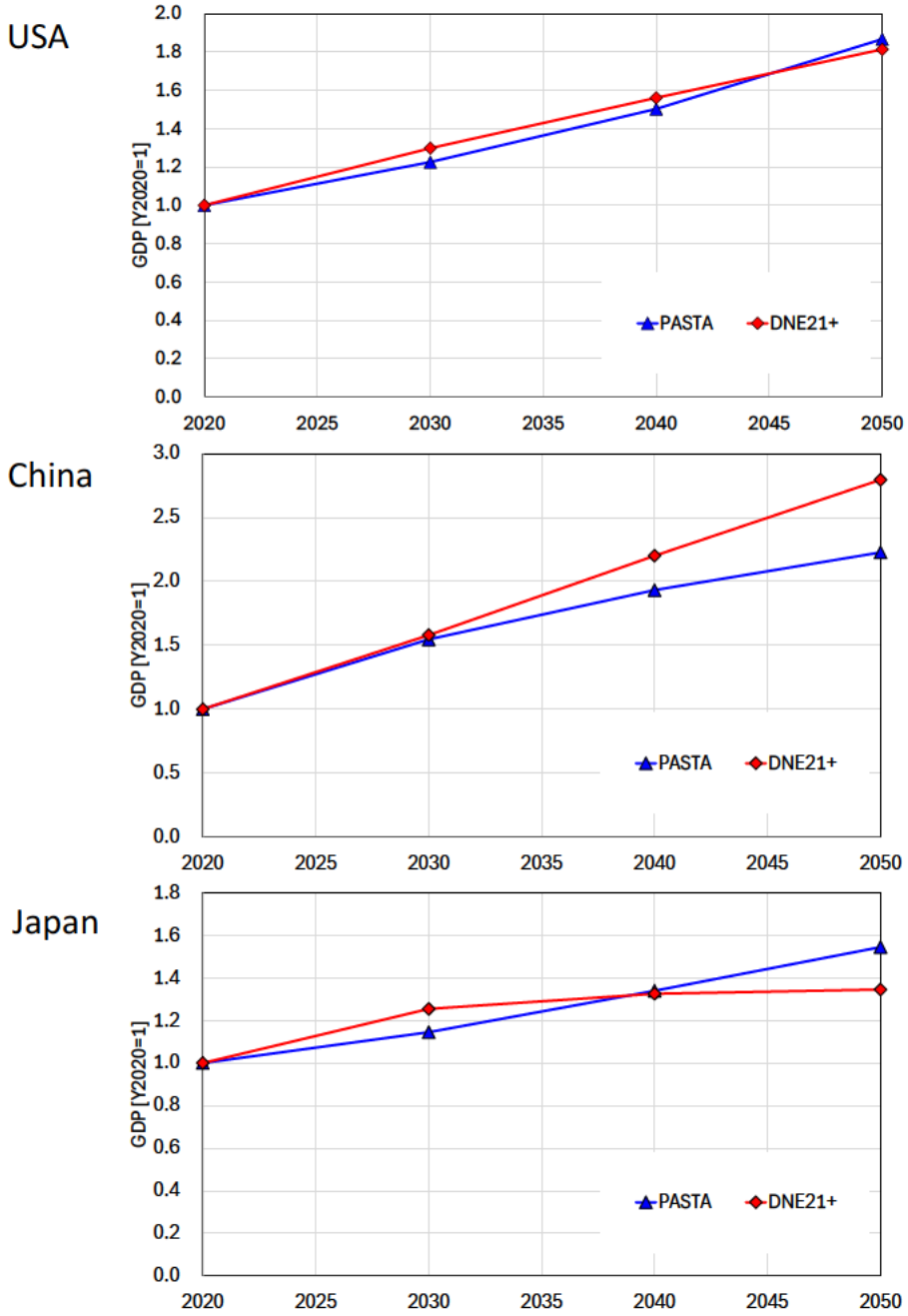


図 3.2-2 DNE21+と PASTA モデルでの GDP シナリオ比較（米国、中国、日本）

図 3.2-3～図 3.2-5 は、道路旅客輸送サービス需要について、人口と同様に、米国、中国、日本の比較を示している。米国については、実績値である 2020 年における需要は、2 つのモデルで概ね一致している。将来の見通しに大きな差異があり、PASTA モデルは、将来の需要が大きく増加すると見込んでいる。中国については、実績値である 2020 年における需要は 2 つのモデルで概ね一致していると共に、将来の見通しにおいても、米国ほどの大きな差異は無い。一方、日本については、実績値である 2020 年における需要から大きな差異があり、今後、モデル間での調整が特に必要と言える（なお、PASTA の日本の道路旅客需要量は、その後、国土交通省の自動車輸送統計データに基づき調整を行った）。

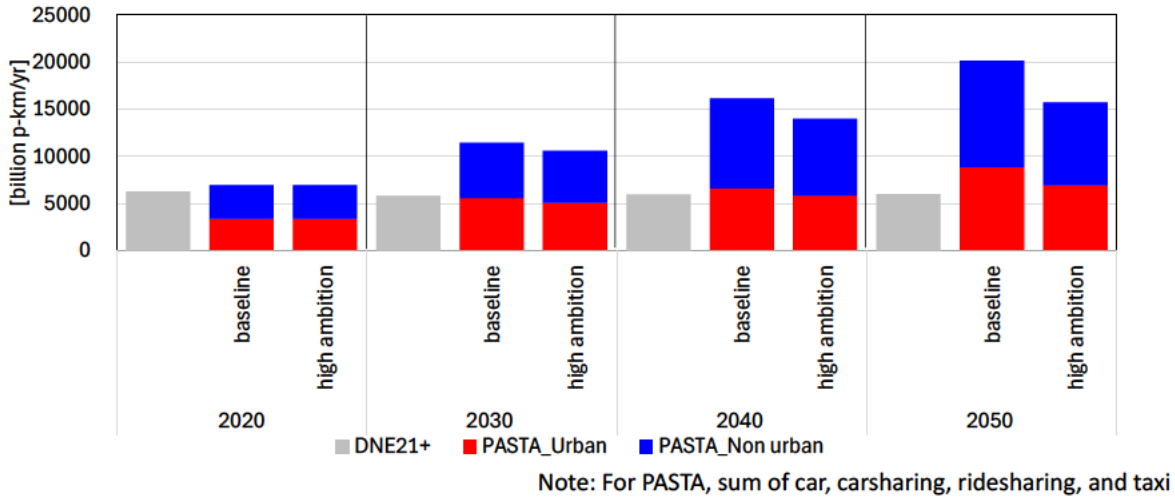


図 3.2-3DNE21+モデルと PASTA モデルでの道路旅客需要シナリオ比較（米国）

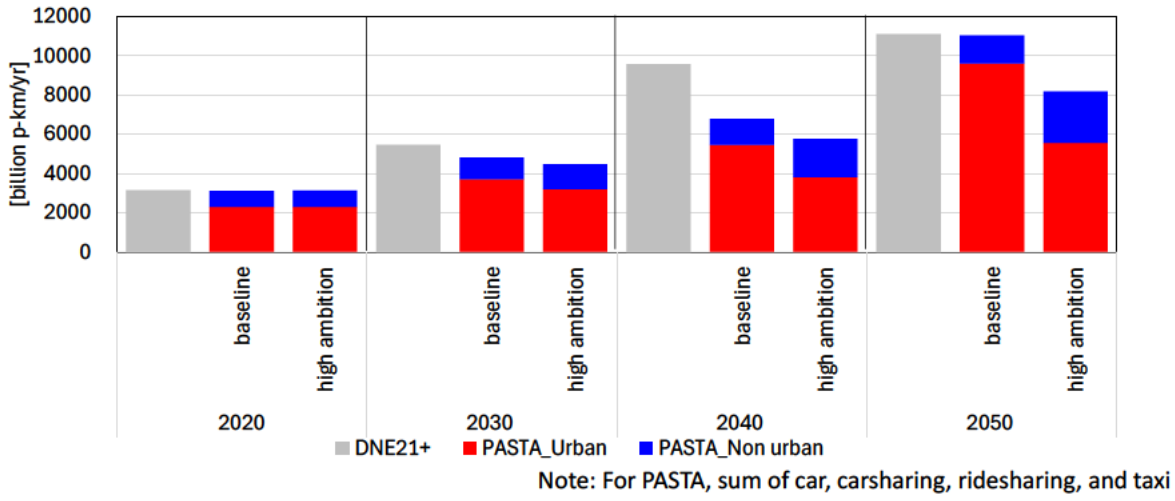


図 3.2-4 DNE21+モデルと PASTA モデルでの道路旅客需要シナリオ比較（中国）

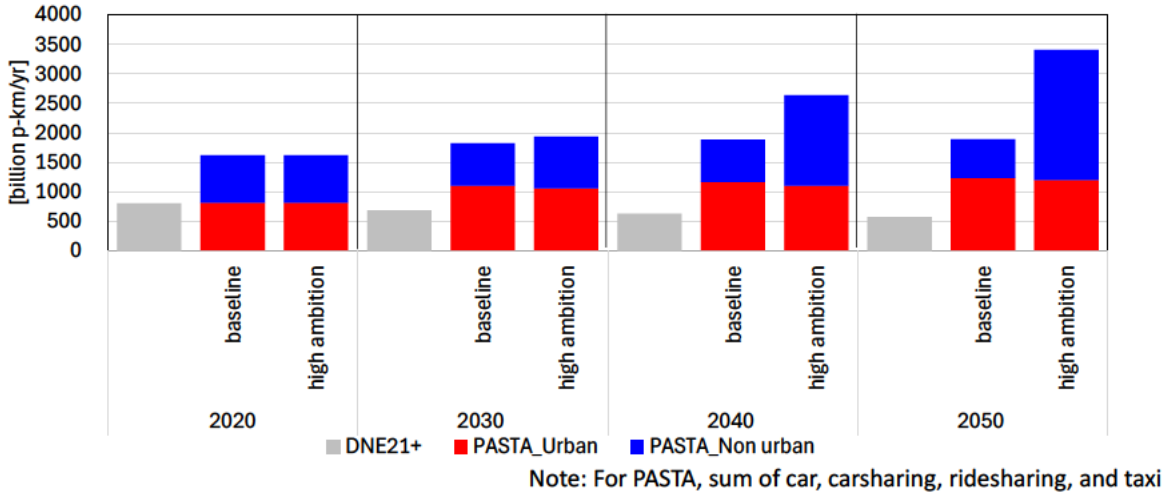


図 3.2-5 DNE21+モデルと PASTA モデルでの道路旅客需要シナリオ比較（日本）

引き続き、シナリオ比較分析を行っていき、査読論文化をしていく必要があるが、実績値の差異は、将来の対策の見通しにも影響し、モデル間で異なるインプリケーション

を導く恐れもあるため、このような調整作業は時間を要するものではあるが、IPCC 第7次評価報告書に向けて重要な取り組みとなると考えられる。

第4章　削減貢献量分析

4.1　削減貢献量の概要

企業の排出量のカウントとして、WRI と WBCSD による GHG プロトコルが広く利用されてきている。Scope 1, 2, 3 が規定されているが、とりわけ Scope 3 は重要であるが、厄介でもある。排出削減に貢献する製品・サービスを提供しても、それが世界で大きく受け入れられれば、自社の Scope 3 排出量は増大してしまう。このような課題意識の下、WBCSD を中心に、“avoided emissions（削減貢献量）”を定義、検討する動きも広がってきている[16]。図 4.1-1 に簡略な“Avoided emissions”の定義のイメージを示す。“Avoided emissions”をより良く定義できれば、グローバルで大きな排出削減を実現する製品・サービスの提供を、より強く企業等の活動にインセンティブとして与えることができる（図 4.1-2 を参照）。しかし、多くの課題もある。そもそも、Scope 3 排出量をカウントするのも、バウンダリーの定義の難しさが存在しているが、“avoided emissions”は排出量の差分に注目するため、Scope 3 排出量のカウントよりも、バウンダリーの課題は幾分か容易であるとも言える。他方、最大の課題は、ベースライン排出量の定義である。ベースライン排出量を過大に想定すると、“avoided emissions”量も過大となり、グリーンウォッシュの懸念が生じてしまう。

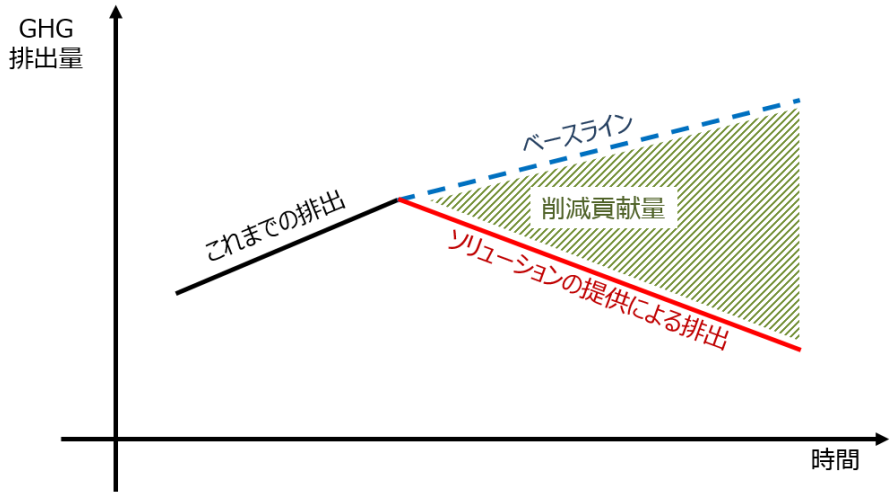


図 4.1-1　削減貢献量（Avoided emissions）とは（定義のイメージ）
（出典：経済産業省[18]）

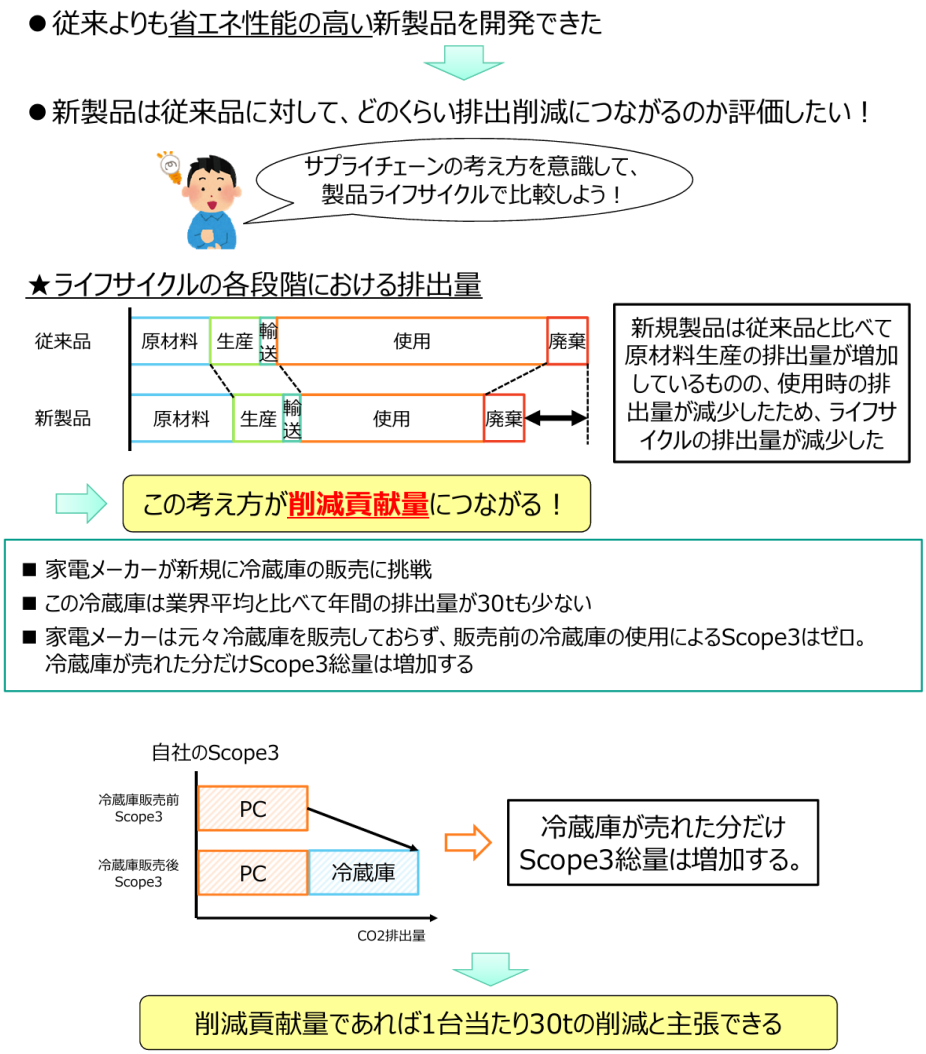


図 4.1-2 削減貢献量（Avoided emissions）の意義

（出典：環境省 [19]）

需要側対策は、製品・サービスを通じて、大きな“avoided emissions”を生み出す可能性がある。本節では、DNE21+モデルを用いた需要部門の対策に関するシナリオ分析を介して、パリ協定長期目標と整合的な“avoided emissions”の将来展望を示す。企業の実績値としてのベースライン排出量の定義には難しさが伴うものであるが、エネルギーシステムモデルを用いた分析では、CO_2 排出削減努力なかりせば、のケースとして、ベースライン排出量は明確に定義できるので、ベースライン排出量の定義の課題は生じない。需要側対策の将来貢献を定量的に示すことによって、需要側対策の“avoided emissions”としての排出削減貢献を見える化し、企業、社会の対応へのインセンティブを働かせることにつながると考えられる。

なお、“avoided emissions”も事前評価（ex-ante evaluation）と事後評価（ex-post evaluation）がある。表 4.1-1 に、“avoided emissions”の事前、事後評価について整理を行った。企業活動の結果として事後評価に焦点があたることが多いし、事後評価は当然重要である。他方、ベースラインの定義が難しいこともあり、グローバルで見て、二重計上がないよう、モデルを用いた事前評価の重要性も高いと考えられる。

表 4.1-1 “Avoided Emissions”の事前、事後評価

	事前評価 (ex-ante evaluations)	事後評価 (ex-post evaluations)
評価方法	モデルを用いた推計	各対策について、普及量等から積み上げて推計
特徴	ベースラインは明確で、追加努力としての削減量を推計可能	グローバルで排出削減に寄与し得る製品・サービスの普及に対して削減貢献量の実績を主張できる
課題	技術毎の詳細な評価は難しい	「対策なかりせば」のベースラインの定義に曖昧さが残りやすく、過大な推計になるのではとの懸念が存在
想定される利用場面	企業等が取り組むべき製品・サービスの削減効果を定量的かつ包括的に示すことができ、企業等の適切な活動の誘発につながり得る。ベースラインの定義に曖昧さが残り、過大な削減貢献量推計への懸念となる事後評価の補間としても利用可能	企業等の製品・サービスを通した取り組みについて、Scope3 では排出増と評価される場合でも、グローバルな排出削減への貢献として、その取り組みの努力等が評価され、アピール材料として活用し得る。

4.2 削減貢献量の概要

本項では、“avoided emissions”として、とりわけ、需要側対策として重要との認識が大きい電化技術の中で、EV（EV バッテリー）、ヒートポンプ冷暖房・給湯機器を取り上げ、DNE21+モデルを用いて世界全体での“avoided emissions”の事前評価を実施した。

4.2.1 分析シナリオの想定

想定した排出削減シナリオは、1.5℃シナリオ（>50%確率）をメインとして、2℃シナリオ（>66%確率）についても評価を行った（以下、それぞれ、B15 シナリオ、WB2 シナリオと表記）。なお、1.5℃シナリオについては、表 4.2-1 で示すように、EV バッテリーのコストに加えて、再エネのコストについての感度解析も実施した。

表 4.2-1 1.5℃シナリオ（B1.5 シナリオ）の感度解析シナリオ

		VREs	
		コスト低減加速	保守的コスト低減
EVs	コスト低減加速	B15	B15_VRE(L)
	保守的コスト低減	B15_EV(L)	B15_(L)

4.2.2 分析結果

まず、図 4.2-1、図 4.2-2 にそれぞれ、1.5℃シナリオ（B15）、2℃シナリオ（WB2）における世界の部門別・技術別の排出削減効果を示す。モデル分析であるため、ベースライン排出量（炭素価格ゼロ）は、モデル上は、明確に定義ができ、経済自律的な排出

削減と、追加的な排出削減は分離されている。発電部門での削減効果は大きいものの、エネルギー需要部門の対策効果も大きく、その対策の強化は重要である。

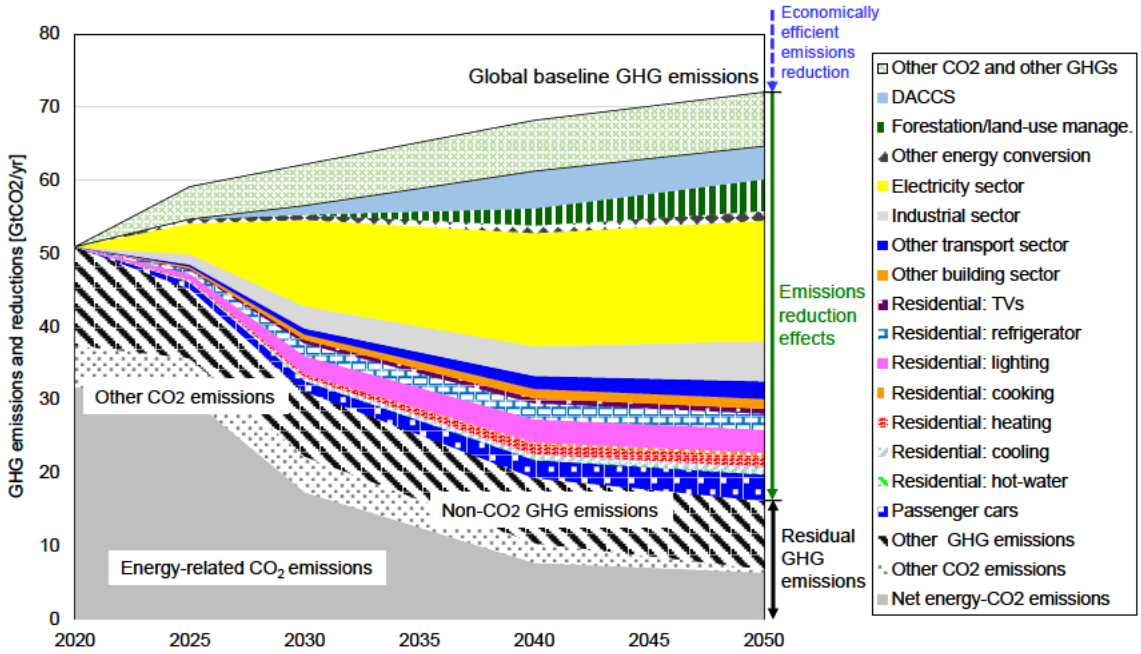


図 4.2-1 1.5℃シナリオ（B15 シナリオ）下の世界における部門別排出削減効果

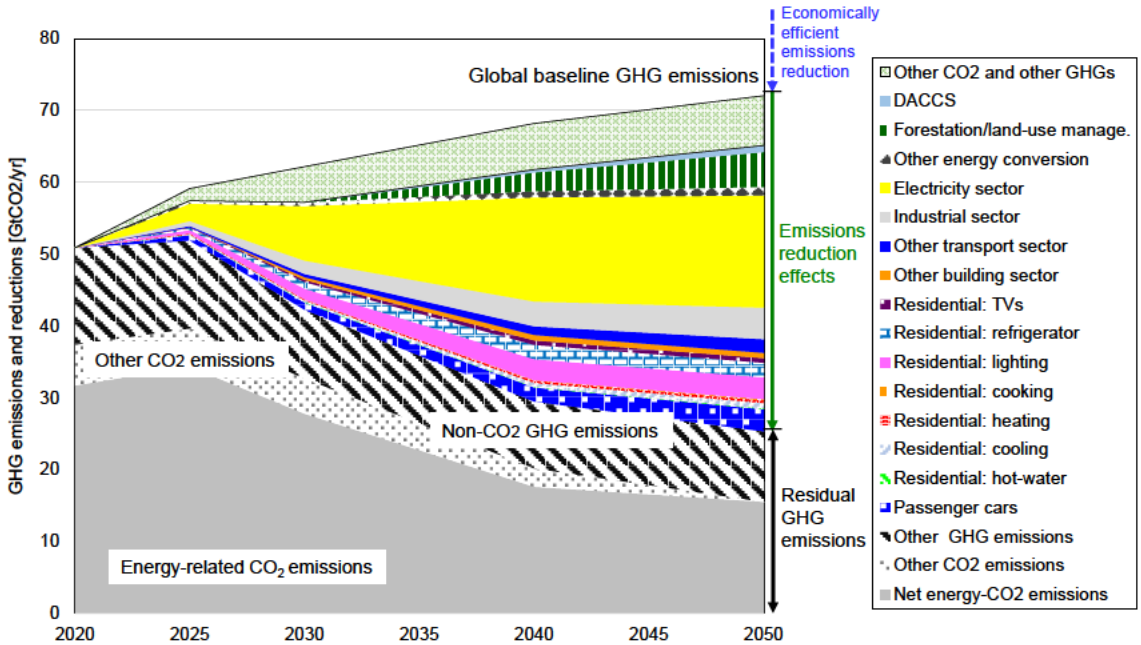


図 4.2-2 2℃シナリオ（WB2 シナリオ）下の世界における部門別排出削減効果

図 4.2-3、図 4.2-4 に、2℃および 1.5℃シナリオ下の世界の乗用車ストック、乗用車の最終エネルギー消費量を示す。また、Scope 2 排出量計算に必要となる、図 4.2-5 に世界の発電電力構成を示す。

図 4.2-3 では、標準シナリオは、EV（EV バッテリー）のコスト低減は楽観的に見込んだシナリオとしたこともあり、比較的大きな導入が見られる。他方、保守的なコスト低減の想定下においては、PHEV、HEV の比率が大きい。

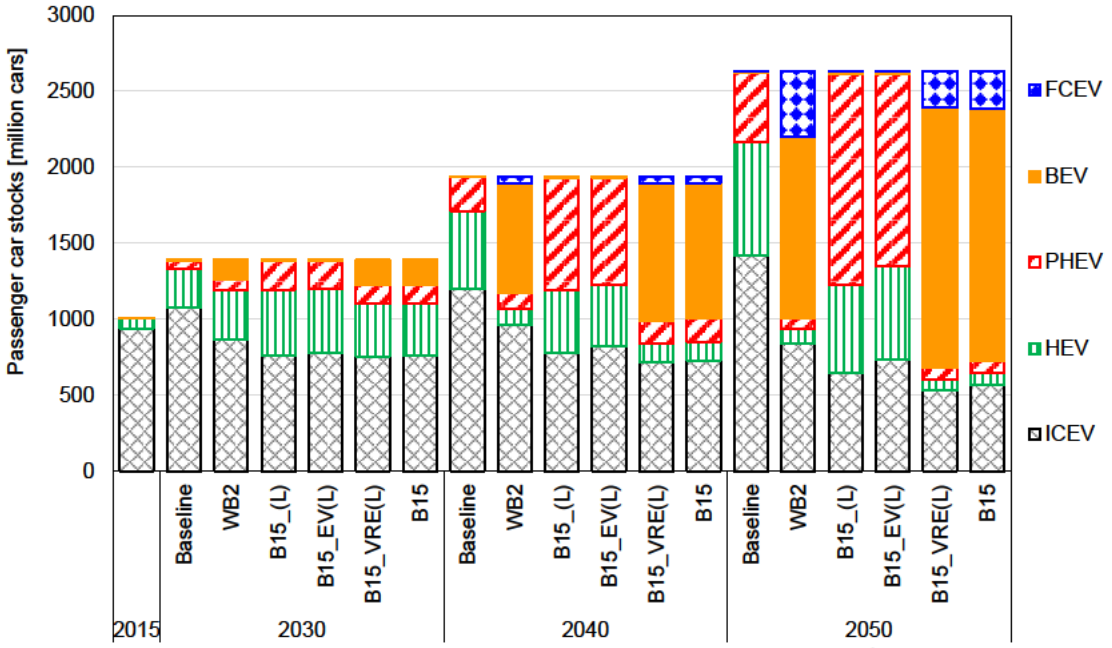


図 4.2-3 2℃／1.5℃シナリオ下の世界における乗用車のストック

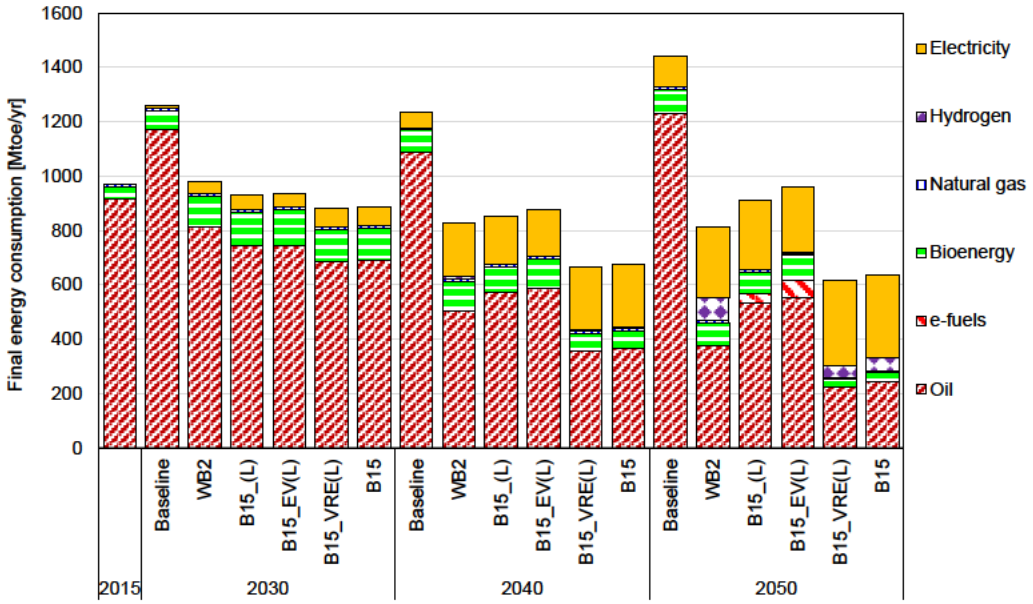


図 4.2-4 2℃／1.5℃シナリオ下の世界における乗用車の最終エネルギー消費量

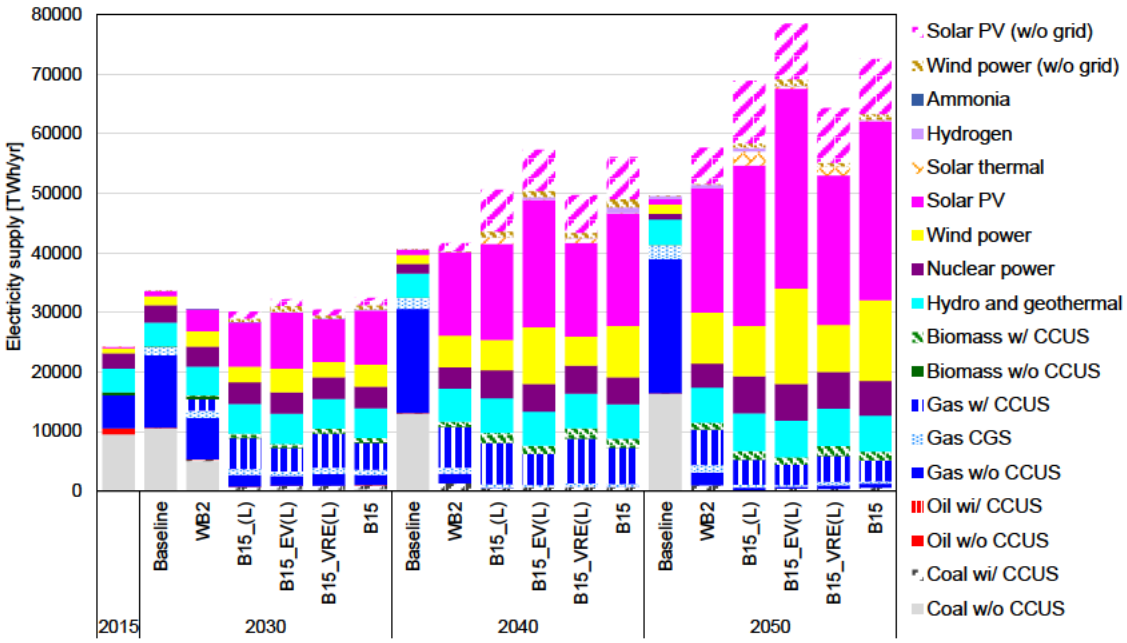


図 4.2-5 2℃／1.5℃シナリオ下の世界の発電電力量

図 4.2-6 に 2℃および 1.5℃シナリオ下の世界排出削減効果を示す。本評価は、各部門での排出削減効果であり、通常の省エネ効果なども含まれている。乗用車の EV 化による排出削減効果は比較的大きい。また、2℃か、1.5℃目標かの違いよりも、EV バッテリーのコスト見通しの違いによる影響が大きい。ヒートポンプ（HP）暖房は、2℃目標下での導入量は小さい一方、1.5℃目標下では導入量が大きくなり、排出削減効果も大きくなっている。HP 給湯については、今回の分析の想定下では、1.5℃目標下でも世界的にはあまり大きな拡大が推計されず、削減効果も比較的小さめと推計された。

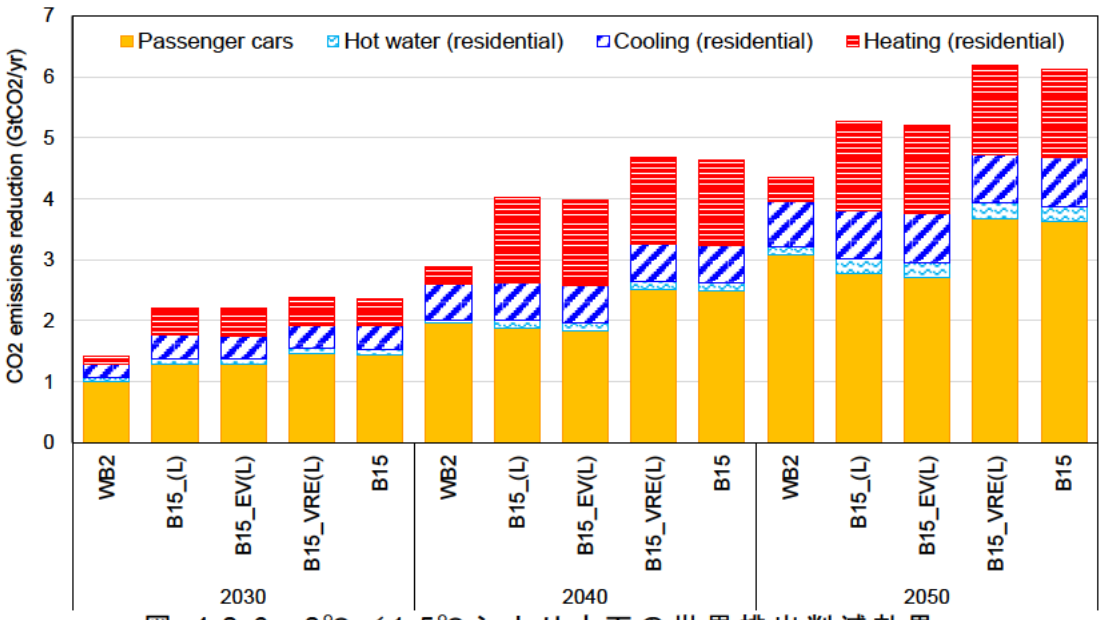


図 4.2-6 2℃／1.5℃シナリオ下の世界排出削減効果：
EV（EV バッテリー）・ヒートポンプ機器等

図 4.2-7、図 4.2-8 にそれぞれ、EV バッテリーと HP 暖房・給湯機器の 1.5℃シナリオ下の累積の世界排出削減効果（排出削減貢献量）を示す。累積削減効果として示しており、“avoided emissions”の定義に合致する推計とした。EV 関係（EV バッテリー）の累積排出削減効果は、2050 年には 12 $GtCO_2$ 程度、HP 暖房・給湯機器関係の累積削減効果は、2050 年には 4 $GtCO_2$ 程度と推計された。大きな削減効果が推計される。

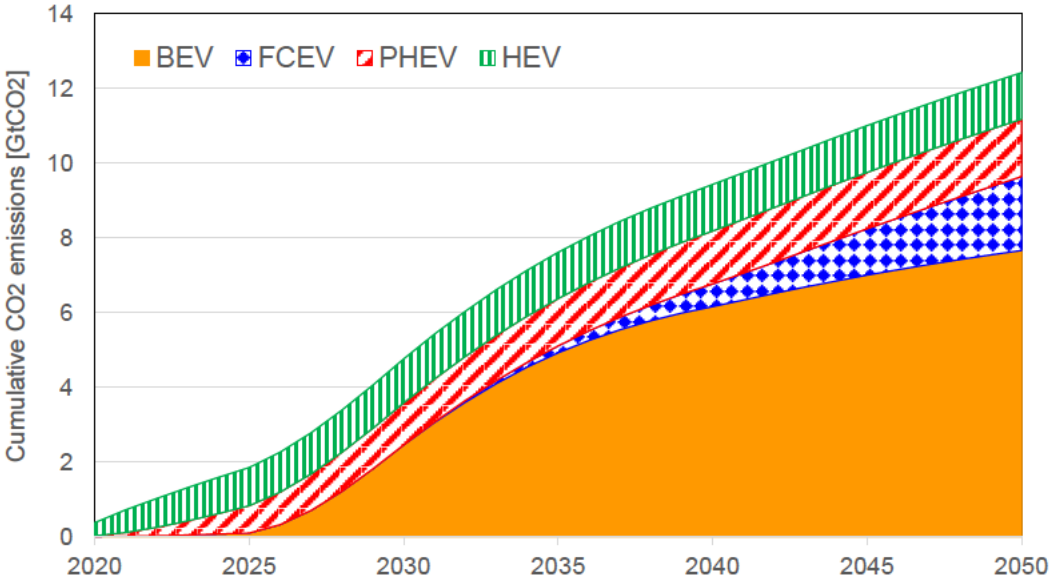


図 4.2-7　1.5℃シナリオ下の累積の世界排出削減効果（排出削減貢献量）：EV（EV バッテリー）関連

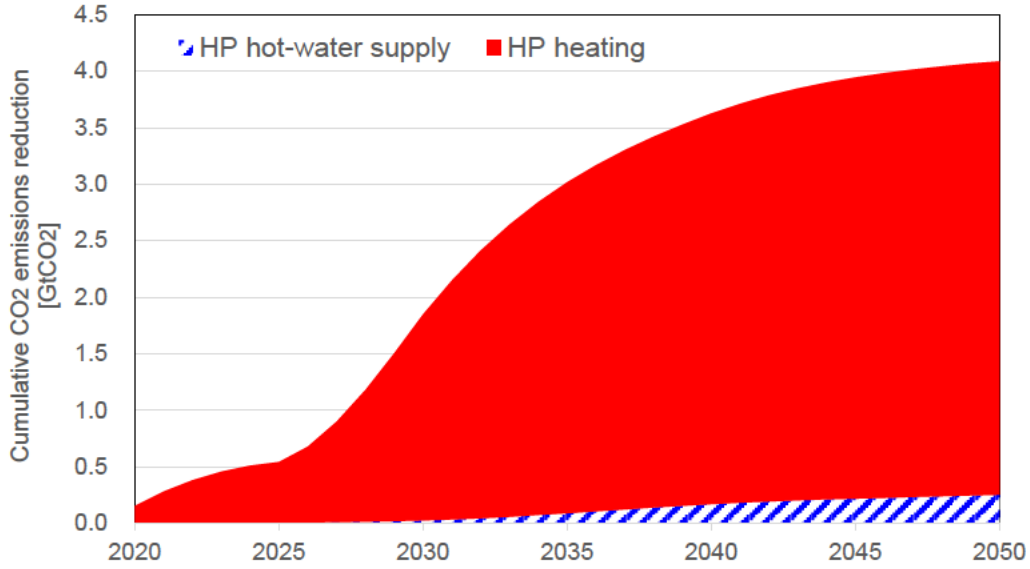


図 4.2-8　1.5℃シナリオ下の世界排出削減効果（排出削減貢献量）：ヒートポンプ関連（HP 暖房、HP 給湯）

このように事前評価として、二重計上なく整合的かつ定量的に、“avoided emissions”を算定し、提示することで、需要側対策の削減行動を促すことに資するものと考えられる。引き続き、分析・評価を実施していく予定である。

第5章　需要側技術を中心とした社会普及障壁に関する分析（コスト・ポテンシャルの理解）

RITE ALPS 事業[13]では、気候変動に関する政府間パネル（IPCC）WG3 で報告されている、部門・技術積み上げ評価と、統合評価モデル IAMs によるコスト・ポテンシャル推計との間に、大きなギャップが存在していることを指摘し、その要因を特定すべく、IAMs の一つであり、かつ部門・技術積み上げ評価を行っている DNE21+モデルを用いて、モデルの想定を変えつつ分析することで、両者の推計が異なってくる要因の特定を行った。本分析は、Energy Strategy Reviews 誌に査読論文として採択された[20]。詳細については、本論文を参照されたいが、本章ではその概要を記す。

5.1.1　IPCC WG3 排出削減コストとポテンシャルと DNE21+分析等との比較

IPCC による第 6 次評価報告書（AR6）[11]では、技術積み上げ評価の結果として、「100 $/tCO$_2$eq 以下のコストの緩和オプションで、世界全体 GHG 排出量を 2030 年までに少なくとも 2019 年レベルの半分に削減しうる。その削減ポテンシャルの半分以上は、20 $/tCO$_2$eq 以下」とした。他方、同じ AR6 では、統合評価モデル（IAMs）による、多数のモデルのシナリオ分析からは、これよりも相当小さな削減ポテンシャルが提示された。また、2018 年に公表された、IPCC 1.5℃特別報告書（SR15）[8]での IAMs シナリオの結果も同様である。

技術積み上げ評価と現実で観測される投資行動、機器選択とのギャップや、技術積み上げ評価と IAMs の分析・評価におけるギャップについては、従来から、主観的割引率（Implicit Discount Rate: IDR）を中心とした論点で、多くの論考が存在する。しかし、IPCC AR6 では第 12 章 Cross-sectoral perspectives においては、技術積み上げ評価と IAMs の分析の差異についての検討はなされているものの、IDR の視点での論考はほとんど見られない。

他方、経済学では「資本のユーザーコスト」という概念が提示されており、資本を利用する際に、経済合理的に、年間支払うべきコストが算定され、経済指標からの具体的な算定も多くなされてきている。しかし、エネルギー、気候変動対策評価の分野では、IDR は比較的議論されるものの、資本のユーザーコストと関連づけた議論はあまり見受けられない。

このような状況において、AR6 のコスト・ポテンシャル推計を中心にしつつ検証・考察した。

図 4.2-1 に、技術積み上げ評価と、各種 IAMs の種類と、それぞれの評価手法における差異について整理を行った。IAMs にも様々存在するが、計量経済モデルや一般均衡モデル（CGE）では、弾性値等の実際の経済活動の指標に基づいてモデル化されるため、観測されるマクロ経済との整合性が重視されることとなる（図中 d）。他方、技術積み上げ型の IAMs も多く存在している（図中 b、 c）。他方、AR6 で整理された部門・技術積み上げ評価は図中 a に位置すると考えられる。

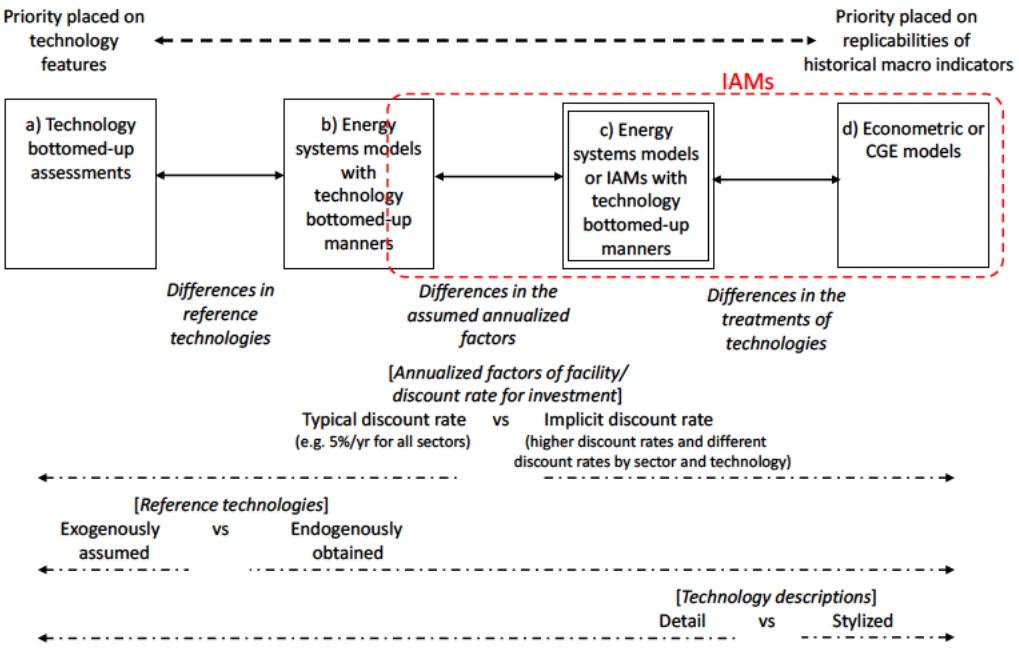


図 4.2-1 コスト・ポテンシャル推計手法とその間の差異

5.1.2 IPCC 第 6 次評価報告書におけるコスト・ポテンシャル推計

本節では、IPCC AR6[11]における世界の排出削減コストとポテンシャル推計について紹介する。IPCC 報告書では、部門別・技術別に排出削減ポテンシャルとコストを積み上げた評価と、統合評価モデル IAMs によるコスト・ポテンシャル推計と 2 種類の推計が示されているが、両者で大きな差異が認められる。表 4.2-1 にその差異の整理を行った。

表 4.2-1 IPCC AR6 における技術積み上げ評価と IAM による評価の差異

		Bottom-up studies (IPCC Fig. SPM7)	IAMs (IPCC Fig. 3.33)
Below 20 USD/tCO_2eq	CO_2	(30.3 $GtCO_2$/yr)	35–45 $GtCO_2$/yr
	GHGs	44.3 $GtCO_2eq$/yr	(49–59 $GtCO_2eq$/yr)
Below 100 USD/tCO_2eq	CO_2	(15.5 $GtCO_2$/yr)	22–33 $GtCO_2$/yr
	GHGs	29.5 $GtCO_2eq$/yr	(36–47 $GtCO_2eq$/yr)

Note: The numbers in parentheses were converted using the difference between GHG and CO_2 emissions in 2019 (14 $GtCO_2eq$/yr).

IPCC AR6 の第 12 章では技術積み上げ評価と IAMs 推計の差異として以下の理由が挙げられている。

【エネルギー供給部門】

- IAMs のシナリオ登録は 2015 年からなされており、最新の太陽光や風力のコスト低減の状況が十分反映されていないため

【民生部門・運輸部門】

- IAMs では負のコストの排出削減ポテンシャルはベースラインに含まれているため

- IAMs ではエネルギーサービス需要の低下やモーダルシフトはあまり想定されていないため

【産業部門】

- 技術積み上げ評価では、資源循環を想定しているケースが多い一方、IAMs の多くでは未考慮なため

【全般】

- 全体として，IAMs では一部の技術について考慮されていないため

しかし、従来からよく議論がなされてきた、主観的割引率など、投資の割引率の問題などについては触れられておらず、十分な理由の説明になっていないと考えられる。

5.1.3 主観的割引率と資本のユーザーコスト

(1) 主観的割引率

実際の投資行動、機器選択行動においては、市場の割引率（たとえば 5%/yr）とは大きなギャップが見られることが知られており、一般的には主観的割引率（Implicit Discount Rate: IDR）として議論がなされてきた。表 4.2-2 に IDR に影響し得る因子の整理を示す。

表 4.2-2 投資の割引率の影響因子例

【技術固有によるもの】 • 技術が必ずしも成熟していない場合（CCS 等）や社会的受容面で課題がある場合（原子力等）は、技術のリスクが高いことから、高い投資リターンが求められる • 製品価値の減耗：新たな製品・サービスへの変化が早ければ、当該製品の価値の減耗は早くなり、割引率は高くなる。逆の場合は低くなる。（電力等エネルギー供給＜鉄、セメント等の素材供給（主にエネルギー多消費産業）＜給湯、空調など（素材供給との大小関係は必ずしも明確ではない）＜ 照明、冷蔵庫など＜テレビ、自動車など） • 将来価格低減が期待できれば、投資を待つことが合理的となり、割引率は高くなる
【投資者、消費者の選好等】 • 資金制約、別の投資先のリターンが高ければ、その期待利益率が参照される • 隠れた費用（投資検討にあたっての機会費用等） • 消費者の選好：環境配慮型製品の購入（アーリーアダプター等）、（住宅等において）コベネフィットの強い認識など • 住宅などで耐用年数よりも居住者の寿命の方が短いと考える場合、割引率は高くなる • オーナー・テナント問題など（民生部門） • 限定合理性（人々の情報処理・判断能力の限界など）
【取引市場、投資環境等、周辺制度によるもの】 • エネルギー・気候変動政策等の不確実性が大きい場合、気候変動対策投資に対して、より大きなリターンが求められる • 炭素価格市場のボラティリティが高ければ、低炭素・脱炭素投資により大きなリターンが求められる • 電力自由化の下、価格指標のボラティリティが大きければ、設備費の大きな電源（低炭素・脱炭素電源）への投資には、より大きなリターンが求められる • 四半期決算などの下では短期の投資回収が志向されやすい

(2) 資本のユーザーコスト

他方、経済学では、資本のユーザーコストという概念での実証研究も行われてきている。Jorgenson の新古典派投資理論において企業の最適化行動を考慮して定式化された資本のユーザーコストは、資本財からのサービスを得るために投資家が支払わなければならない費用として定義され、次式で表される（一部、簡略化して表示）。機器のレンタル価格にも相当する。資本取得価格（P_t^A）に対する係数（$r_{kjt}+\delta_{kj}-\pi_{kt}$）は通常、年次化要素（annualization factor）と呼ばれる。

$$P_{kjt}^K = (r_{kjt} + \delta_{kj} - \pi_{kt})P_{kt}^A$$

資本のユーザーコスト（P_t^K）、資本取得価格（P_t^A）、t 時点における実質利子率等（r_t）、減価償却率（δ）、資本財価格の変化に伴うコスト（π）、資産の種類（k）、国あるいは経済主体（j）

重要な点は、年次化要素すなわち資本を得るために毎年支払うコストは、利子率（r）だけで構成されず、資本の減耗率（減価償却率）（δ）と資本財価格の変化に伴うコスト

（π、価格低下が期待されるときコストとなる）を含む点であり、利子率だけではなく、これら 3 つの要素を含めた投資判断が経済合理的と考えられるものである。つまり、利子率（r）が 5%/yr だったとしても、減耗率（δ）が 20%/yr であれば（πは 0 とした場合）、投資の割引率に相当する年次化要素は 25%/yr となる。

5.1.4 DNE21+によるコスト・ポテンシャル試算結果

本節では、特に投資の割引率に注目して、DNE21+モデルを用いて、世界のコスト・ポテンシャル推計を行い、それを、IPCC AR6 の IAMs 評価と比較し、その上で、同じく AR6 の部門別・技術別の積み上げ評価結果とほ比較を記載する。

表 4.2-3 に、DNE21+において標準想定の投資の割引率とした場合と、投資の割引率を地域・国、部門・技術を横断的に一律 5%/yr と想定した場合の 2030 年の世界の排出削減コスト・ポテンシャル推計を示す。表 4.2-3 にはあわせて AR6 における積み上げ評価と IAMs 評価の結果も比較として示している。DNE21+の標準想定の投資の割引率での推計は、IPCC IAMs の推計と近い一方で、投資の割引率を地域・国、部門・技術を横断的に一律 5%/yr と想定した場合は、IPCC AR6 の積み上げ評価における割引率想定と近い想定と考えられ、DNE21+の分析結果も近くなっている。割引率の想定の違いが差異に関する一つの大きな要因と考えられる。

表 4.2-3 IPCC AR6 における技術積み上げ評価と IAM、DNE21+による世界のコスト・ポテンシャル推計（2030 年）

	Bottom-up studies (IPCC Fig. SPM7) †	IAMs (IPCC Fig. 3.33)*	DNE21+	
			Standard discount rate	Low discount rate of 5%/yr ‡
Below 20 USD/tCO_2	Around 14 $GtCO_2$/yr	Around 2 $GtCO_2$/yr	4.2 $GtCO_2$/yr	7.1 $GtCO_2$/yr
Below 50 USD/tCO_2	–	Around 7–10 $GtCO_2$/yr	9.0 $GtCO_2$/yr	13.4 $GtCO_2$/yr
Below 100 USD/tCO_2	29 $GtCO_2$/yr (24–36 $GtCO_2$/yr)	Around 10–15 $GtCO_2$/yr	14.0 $GtCO_2$/yr	18.1 $GtCO_2$/yr
Below 200 USD/tCO_2	–	Around 15–20 $GtCO_2$/yr	19.8 $GtCO_2$/yr	24.7 $GtCO_2$/yr

† For the bottom-up studies of IPCC, the potentials in CO_2 are simply converted using the emission gap in 2019 between CO_2 and GHG (76%).

‡ The baseline emission of the standard discount rate case is employed for the emissions reduction potentials under the 5% discount rate case.

* Figure 3.33 shows the global CO_2 emissions and marginal abatement costs (carbon prices) for the IAM scenarios, which include various different models and different assumptions, and the consistent emissions reduction within each IAM is not clear. The numbers are rough estimates from the figure.

図 4.2-2 に、IPCC の技術積み上げ評価と IAMs の推計、そして、DNE21+における標準の投資の割引率想定時の 5%/yr で地域・部門一律に想定した場合との比較（エネルギー供給、産業、運輸、建物別）結果を示す。5%/yr の割引率想定時には、運輸、建物部門での差異が縮まる一方、エネルギー供給部門、産業部門では大きな差異が残っていることが確認できる。

エネルギー供給部門の差異については、更に、DNE21+モデルにおける、系統統合費用をゼロと想定した場合について、感度解析を実施した。このとき、図 4.2-3 に示すように、AR6 における技術積み上げ評価での太陽光、風力発電のコスト・ポテンシャル推計を超える経済的ポテンシャルが推計される。すなわち、エネルギー供給部門は他の部門と比べ相対的には割引率が小さいため、IPCC の技術積み上げ評価で主に用いられている 5%/yr との差は小さく、割引率の差による部分はそれほど大きくはない。ポテンシャルが大きく推計されているのは、AR6 における技術積み上げ評価で系統統合費用が想定されていないことが大きな理由と考えられる。

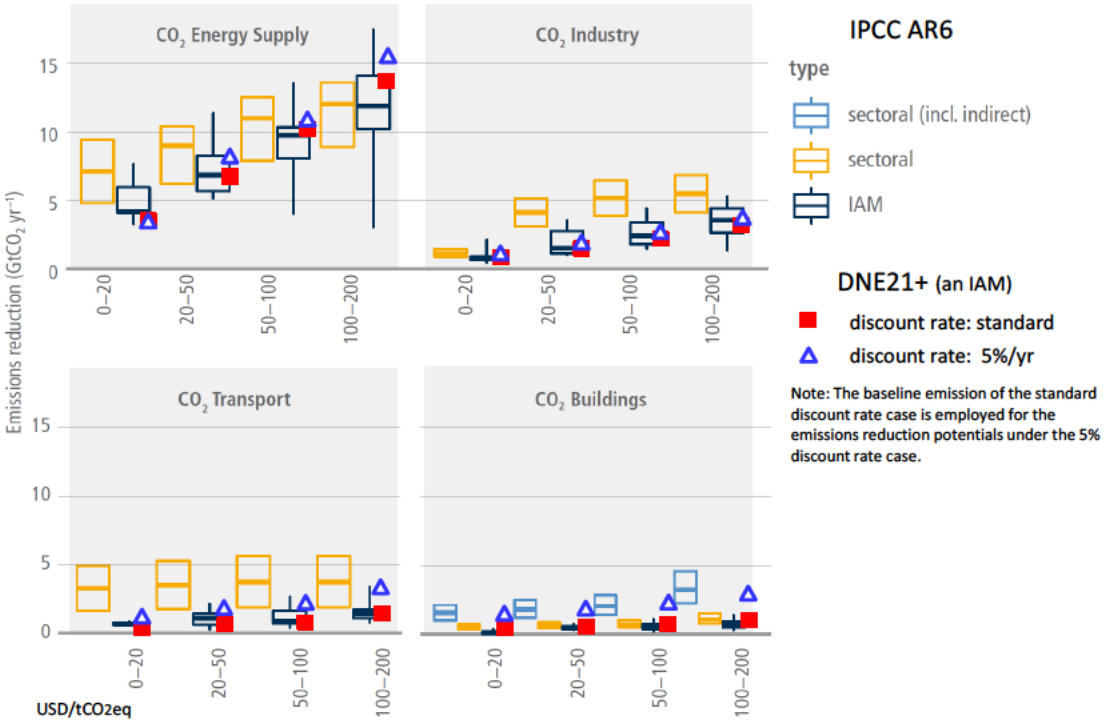


図 4.2-2 技術積み上げ評価と IAMs 評価の差異

（出典：文献 11)を基に加工）

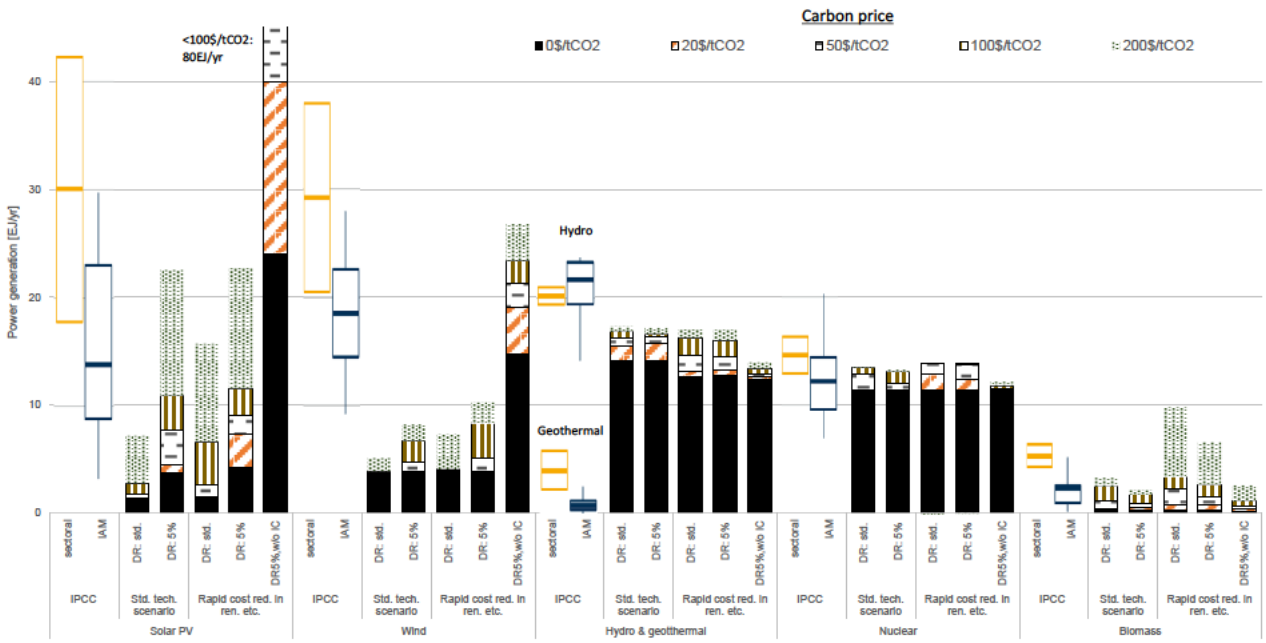


図 4.2-3 技術積み上げ評価と IAMs 評価の差異：脱炭素エネルギーの導入見込み量
（出典：文献 11)を基に加工）

IPCC 報告書が提示した部門･技術積み上げの排出削減ポテンシャル･コスト推計は、低コストでかなり大きな排出削減ポテンシャルを提示している。しかし、世界排出量は増大しているほか、実態とかけ離れた推計と見られる。また、同じ IPCC 報告書でも、統合評価モデル IAMs は、保守的な排出削減ポテンシャルを推計しており、大きな乖離が見られる。

従来から、部門・技術積み上げの排出削減ポテンシャル・コスト推計は過大な排出削減ポテンシャルを示すことは指摘されてきていて、とりわけ「主観的割引率（IDR)」によって説明がなされてきた。他方、気候変動対策の研究コミュニティーでは、あまり議論がなされないものの、「資本のユーザーコスト」として、より経済全般にわたる整合性との関係から投資の割引率が以前から議論がなされ、各種計測もなされている。

本研究では、技術積み上げ評価モデルである DNE21+の推計が、IPCC 報告書の IAMs 推計の中位的な推計結果を示していることを確認した上で、投資の割引率の想定を、国・部門・技術・利用者によって差異のある割引率から、部門・技術積み上げ評価でよく利用される、5%/yr で一律に設定した場合の試算を実施した。このとき、とりわけ、運輸部門の推計は、 IPCC 報告書が提示した部門･技術積み上げの排出削減ポテンシャル・コスト推計に近づくことを確認した。そして、本分析等を踏まえると、(IPCC AR6 などで示されている）技術積み上げ評価と IAMs 推計の差異の主要な理由として以下が考えられ、これは、IPCC AR6 記載の理由とは必ずしも合致しないものである。

【全般】

- 全体として、技術積み上げ評価では、現実の社会に存在している、様々な技術普及障壁が考慮されていないため

【エネルギー供給部門】

- 技術積み上げ評価では、太陽光や風力発電の系統統合費用が考慮されていないため

【民生部門・運輸部門】

- IAMs では負のコストの排出削減ポテンシャルはベースラインに含まれているにも関わらず､技術積み上げ評価では IAM のベースライン排出を利用しており、技術積み上げ評価ではダブルカウントしているため
- IAM で低割引率想定をすると、電化の対策（EV、HP 暖房・給湯、CGS など）がより進展する結果とはなるが、現実には初期費用が高い技術は導入されにくい。

【産業部門】

- 技術積み上げ評価では、資源循環を想定しているケースが多い一方、IAMs の多くでは未考慮なため、IAMs では削減ポテンシャルを過小評価しているかもしれない。他方、技術積み上げ評価では、世界全体での鉄スクラップ量の制約などが未考慮であって、技術積み上げ評価の方が、現実よりも過大な削減ポテンシャル推計となっている可能性も十分に高い。

排出削減ポテンシャル・コスト推計は、技術選択、政策検討の基礎となるもの。誤った理解に基づく推計は、コスト効率的な対策、そしてそのための政策を歪めかねない。「隠れたコスト」が生じている要因は何なのかを正しく理解することが、効率的な政策、対策をとるための一助となる。

少なくとも、例えば 5%/yr で一律に設定した投資割引率を用いた、部門・技術積み上げの排出削減ポテンシャル・コスト推計を、部門横断的に集計することは大きな誤解を生むので、行うべきではないだろう。

第6章　まとめと今後の課題

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、一次試算を行ってきた。ただし、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。他方、これらの分析を複数モデルによって比較評価するには、モデル間の調整等に時間を要する。

そこで、本年度は、道路交通部門に限定し、RITE、OECD-ITF、IIASA による複数モデルで比較評価を試みた。しかし、それでもモデルで想定している実績値の違いが顕著である場合もあり、その調整を行った。地道な作業であるが、査読論文化するために必要な作業であるとともに、将来推計において、障壁と機会をより正しく評価していくことにもつながると考えられる。

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 AR6 の評価で見られた、積み上げ評価と統合評価モデル IAM のコスト・ポテンシャル推計の大きな幅についても、別途、ALPS 事業で分析を行ったが、EDITS 事業へも展開し、国際的な理解促進につなげた。ここでも、障壁と機会をより正しく理解し、低エネルギー消費を実現するために、必要な対策、制度の議論を促し得る成果と考えられる。

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。

参考文献

1) COP28, Decision -/CMA.5 Outcome of the first global stocktake (2023) https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf
2) 日本政府、「地球温暖化対策計画」(2025) https://www.env.go.jp/earth/ondanka/keikaku/250218.html（最終アクセス日 2025 年 2 月 20 日）
3) 日本政府、「日本の NDC（国が決定する貢献）」(2025) https://www.env.go.jp/content/000291804.pdf（最終アクセス日 2025 年 2 月 20 日）
4) 日本政府、「第 7 次エネルギー基本計画」 (2025) https://www.meti.go.jp/press/2024/02/20250218001/20250218001.html（最終アクセス日 2025 年 2 月 20 日）
5) 日本政府、「GX2040 ビジョン」(2025) https://www.meti.go.jp/press/2024/02/20250218004/20250218004.html（最終アクセス日 2025 年 2 月 20 日）
6) G7 札幌 気候・エネルギー・環境大臣会合成果文書 (2023) https://www.meti.go.jp/press/2023/04/20230417004/20230417004.html
7) G7 トリノ 気候・エネルギー・環境大臣会合成果文書 (2024) https://www.env.go.jp/press/press_03143.html
8) IPCC, Special Report on Global Warming of 1.5 C (2018)
9) A. Grubler et al. A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. Nat. Energy, 3(6), 515–527 (2018)
10) C. Wilson et al., Granular technologies to accelerate decarbonization. Science, 368(6486), 36–39 (2020)
11) IPCC WG3, 第 6 次評価報告書 (2022)
12) RITE, 経済産業省委託 2024 年度地球温暖化対策技術の分析・評価に関する国際連携事業（ALPS）報告書 (2025)
13) RITE, 経済産業省委託 2023 年度地球温暖化対策技術の分析・評価に関する国際連携事業（ALPS）報告書 (2024)
14) C. Wilson, L. Kerr, F. Sprei, E. Vrain, M. Wilson, Potential Climate Benefits of Digital Consumer Innovations. Annu. Rev. Environ. Resour., 45(1) (2020)
15) EDITS WG3 Narratives group (Arnulf Grubler, Greg Nemet, Shonali Pachauri, Charlie Wilson), The 'High-with-Low' Scenario Narrative (2022)
16) Akimoto, K., Sano, F., Oda, J., 2022b. Impacts of ride and car-sharing associated with fully autonomous cars on global energy consumptions and carbon dioxide emissions. Technological Forecasting and Social Change 174, 121311. https://doi.org/10.1016/j.techfore.2021.121311
17) WBCSD (2023). https://www.wbcsd.org/Imperatives/Climate-Action/Resources/Guidance-on-Avoided-Emissions

18) 資源エネルギー庁 (2023) https://www.enecho.meti.go.jp/about/special/johoteikyo/sakugenkokenryo.html
19) 環境省「削減貢献量について」
https://www.env.go.jp/earth/ondanka/supply_chain/gvc/files/SC_syousai_Option1_20230301.pdf
20) K. Akimoto, M. Nagashima, F. Sano, T. Ando, Gaps between costs and potentials estimated by bottom-up assessments versus integrated assessment models, Energy Strategy Reviews, 55, 101521 (2024).

Nexus
Perspective

Energy sufficiency for deep decarbonization: A modeling framework

Jingjing Zhang,[1,*] Michelle Johnson-Wang,[1,2] Nina Khanna,[1] Max Wei,[1] Bianka Shoai-Tehrani,[3] and Nan Zhou[1]
[1]Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[2]University of California, Berkeley, Berkeley, CA, USA
[3]Réseau de Transport d'Electricité (RTE), Research and Development Division, Paris, France
*Correspondence: jingjingzhang@lbl.gov
https://doi.org/10.1016/j.ynexs.2025.100055

BROADER CONTEXT

Deep decarbonization requires a robust framework to model and realize energy sufficiency, which provides energy services that support global social foundations operating within ecological limits. Current models either exclude energy sufficiency or combine it with energy efficiency, obscuring its unique benefits. This paper introduces the decentralization, right-sizing and reduction, utilization/timing and longevity, multifunctionality, substitution, and sharing (DRUMSS) framework, which provides definitions and boundaries for modeling sufficiency. DRUMSS identifies ways to establish energy sufficiency and to estimate the associated climate mitigation potentials. The framework supports both the scientific study and practical application of energy sufficiency. Three international case studies describe practical actions and policy levers for furthering sufficiency. The DRUMSS framework requires interdisciplinary collaboration to augment the indicators and data needed to communicate the benefits of sufficiency measures.

ABSTRACT

This work explores the concept and modeling of energy sufficiency, differentiating it from energy efficiency. Both elements are vital to rethinking established systems of production and consumption in the face of energy crises and climate change. The developing field of energy sufficiency can potentially constrain energy use within planetary resources while meeting humanity's needs. Current energy and climate models generally exclude energy sufficiency, however, or combine it with energy efficiency, obscuring its distinct benefits. Theoretical frameworks, such as avoid-shift-improve, lack clear definitions and boundaries between sufficiency and efficiency measures.

This paper introduces the decentralization, right-sizing and reduction, utilization/timing and longevity, multifunctionality, substitution, and sharing (DRUMSS) framework to improve the modeling of energy sufficiency. DRUMSS provides steps for implementing sufficiency measures across demand-side sectors, identifying policy actions to achieve deep decarbonization. We present three case studies, from the United States, China, and France, to illustrate implementing the DRUMSS framework in diverse contexts.

INTRODUCTION

Researchers and policymakers generally agree that reducing energy demand is crucial for addressing the climate crisis. Numerous studies have indicated that energy demand can be lowered while achieving well-being using current technologies.[1–3] In 2022, the Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6) introduced a sufficiency, efficiency, renewable framework. AR6 defines sufficiency as decreasing the demand for materials, energy, land, water, and other natural resources while delivering a comfortable living standard for all people.[4,5] Although authors differ in emphasis, the consistent theme in the literature is that sufficiency provides energy services in support of global social foundations operating within ecological limits,[6–8] particularly emphasizing the concept of "enoughness."[9]

The concepts of sufficiency and efficiency often are used interchangeably, obscuring their distinct roles in climate mitigation. Earlier work defined energy efficiency as lowering energy input for a given service without necessarily reducing overall energy demand, whereas energy sufficiency concerns reducing energy input by changing the product or service that consumes energy.[10]

The concept of sufficiency has been a principle for economic development. For example, the Xiaokang society (or moderately prosperous society), introduced in China in 1979, emphasizes equity and comfortable living over pure economic growth. Although energy sufficiency also addresses overconsumption and encourages moderation, in the context of climate change, we view sufficiency as a decarbonization pathway rather than as a value-based philosophy. Regarding climate mitigation and energy security, significant scholarly work has provided philosophical justifications, frameworks, policies, and data in support of sufficiency.[11–14]

Various authors have modeled the effects of sufficiency measures, one estimating that they provided reductions as great as 48% in energy and 54% in greenhouse gas (GHG) emissions in the building sector.[15]

Although sufficiency is discussed more widely today, we lack a uniform understanding of operationalizing sufficiency.[11] Recent energy models and tools that incorporate low energy demand solutions consider a small number of sufficiency measures.[2,16–19] Although sufficiency now is incorporated more in energy modeling, few studies consider a comprehensive suite of sufficiency measures, overlooking opportunities for deep decarbonization. Additionally, modeling scenarios have focused primarily on lifestyle and behavioral changes, which are critical for deep climate mitigation, but also require the support of enabling policies, infrastructure, and technologies.

This paper introduces a framework for modeling energy sufficiency, along with indicators, to fill knowledge gaps, develop methods for identifying sector-specific actions, and enhance models' ability to quantify potential impacts of sufficiency. Our framework is called decentralization, right-sizing and reduction, utilization/timing and longevity, multifunctionality, substitution, and sharing (DRUMSS). Unlike the avoid-shift-improve (ASI) framework, which considers energy efficiency, sufficiency, and fuel-switching actions, the DRUMSS framework concerns only sufficiency actions identified throughout temporal and spatial dimensions. It also fills a key gap: that current models fail to display the causal chains needed to realize robust decarbonization potentials.[20]

We detail six pillars of the DRUMSS framework using examples in four sectors: building, transport, industry, and cross-sector, highlighting policy, technology, infrastructure, and behavioral enablers for each. Finally, the paper calls for proactive efforts to change systems of production

© 2025 The Authors. Published by Elsevier Inc. on behalf of The Hong Kong Polytechnic University.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

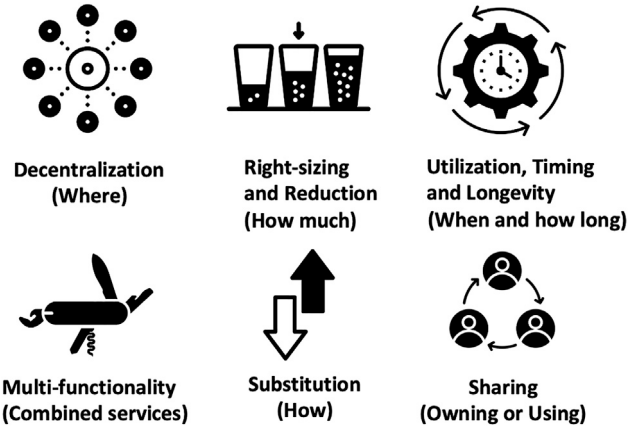


Figure 1. DRUMSS framework
All icons used in the figure are from thenounproject.com CC BY 3.0).

and consumption toward energy sufficiency, integrating this concept in policy, research, and everyday life.

THE DRUMSS FRAMEWORK

Although multiple researchers have proposed frameworks for modeling sufficiency,[13,20–23] those frameworks failed to account for the nuances of mitigation potentials at spatiotemporal scales, as well as population heterogeneity. For example, sufficiency emphasizes reduction, but many low-income households worldwide possess insufficient goods and services to reach the minimum social foundation. The frameworks did, however, initiate a re-evaluation of the boundaries between sufficiency typologies: whether each category is distinct, whether a typology overlaps with efficiency, and whether a typology applies to all countries.

Our DRUMSS framework incorporates six actionable pillars—decentralization; right-sizing and reduction; utilization, timing, and longevity; multifunctionality; substitution; and sharing—that support energy sufficiency (Figure 1). Using the DRUMSS framework, we explore effects on consumer well-being from measures that further energy sufficiency, rather than efficiency, while providing environmental benefits. We also provide examples of technology and policy solutions to render sufficiency more actionable. Lastly, we include potential quantitative indicators for energy consumption under sufficiency, based on the Kaya identity, noting additional data needs for modeling energy and emission impacts and quantifying sufficiency's full benefits. The six pillars of sufficiency, illustrated in Figure 1, are described below.

Decentralization reduces energy and environmental impacts by changing the format in which a consumer receives an energy service. Decentralization focuses on localizing consumption. Buying locally produced seasonal foods (e.g., through farmers' markets) or locally made goods rather than imported products reduces the embodied energy and emissions of those items. Choosing to travel for leisure locally rather than long-distance reduces operational energy demand for transportation. Of course, the availability of local choices for leisure and produce are key enabling conditions. Table 1 presents examples and indicators of decentralization in buildings, transportation, industry, and cross-sector activities.

Right-sizing and reduction is one aspect of sufficiency that distinguishes it from energy efficiency. This pillar, which encompasses the concept of enoughness, refers to consumers choosing (and being enabled to choose) the appropriate size, amount, and usage of energy products/services. An energy service is still required, and the same product or service may be consumed, but right-sizing reduces energy demand in cases of over-consumption while increasing it for under-consumption. In the building sector, right-sizing may include adjusting the thermostat to a more moderate temperature or matching the size of an appliance with the need (e.g., refrigerator capacity, television screen size, water heater capacity). A frequently mentioned right-sizing strategy involves reducing living space, incorporating smart design, and affordability. An older couple moving from a single-family home to a smaller apartment exemplifies right-sizing and reduction. Their new lifestyle incorporates enoughness and potentially increased financial freedom and improved well-being. Table 1 presents examples and indicators of right-sizing and reduction in buildings, transportation, industry, and cross-sector activities.

Utilization, timing, and longevity enhances the well-being derived from products and infrastructure through design and behavioral changes. Examples include doing laundry or showering less frequently or purchasing seasonal fruits and vegetables. Timing could mean operating buildings or equipment during set periods to minimize waste. Behavioral adjustments can extend longevity—proper food storage extends its shelf life and reduces waste. Extending the operational lifespan of appliances reduces the need for repair and avoids the energy embodied in manufacturing replacements. Although the energy service remains the same, altering frequency and intensity of use can maximize the utility of a given product or structure. If manufacturers are incentivized to produce more durable products and offer replacement parts and/or maintenance support, products can be repaired instead of discarded. Extending the longevity of buildings significantly reduces embodied carbon by decreasing demand for new buildings construction. Table 1 provides examples and indicators of utilization, timing, and longevity in buildings, transportation, industry, and cross-sector activities.

Multifunctionality optimizes resources through designs that furnish multiple services. Although the mode of delivery of energy services may be altered, the service is not. For example, a product that is able to both heat/cool and purify air has less embodied energy, and potentially less operational energy, than separate heating, air conditioning (AC), and air purifying systems. Another method is digital convergence,[24] such as a smartphone that replaces 17 or more devices, from alarm clocks to the Global Positioning System and radios, with 30 times less power in use and 100 times less power in standby.[16] Table 1 presents examples and indicators of multifunctionality in buildings, transportation, industry, and cross-sector activities.

Substitution changes the mode in which an energy service is received. Unlike demand-reduction frameworks such as ASI, our framework excludes electrification, a feature of energy efficiency, instead, viewing substitution as mode shifting. In the DRUMSS framework, substitution calls for changing behavior and/or cultural norms rather than actions. For instance, in the building sector, passive cooling reduces the need for AC, while natural lighting reduces lighting electricity use. Behavioral changes may involve layered clothing and heated blankets to reduce centralized heating or air drying instead of machine drying. Walking or biking instead of driving represents substitution in the transportation sector. To support such fundamental changes, public and societal support is needed, along with institutional and policy enablers such as incentives for passive house design, zoning reforms, and availability of pedestrian walkways and bike lanes. Table 1 provides examples and indicators of substitution in buildings, transportation, industry, and cross-sector activities.

Sharing, which has received less attention than the other pillars of sufficiency, involves utilizing a service or product to its full capacity through shared use, rather than individual ownership. Sharing reduces operating and/or embodied energy and emissions. Sharing actions exist across all consumption sectors, such as communal living and work spaces, appliance and tool sharing, carpooling or ride-sharing, and shared commercial kitchens. Programs and policies already promote sharing in some sectors, such as benefit programs for carpooling (e.g., high-occupancy lanes). In California, the city of Berkeley's tool lending library illustrates a sharing practice. For shared mobility, tracking indicators such as the percentage of shared rides out of total trips are fairly straightforward, but energy savings are more difficult to quantify for shared appliances, tools, or meal preparation. Table 1 provides examples and indicators of sharing in buildings, transportation, industry, and cross-sector activities.

CASE STUDIES

To demonstrate implementing sufficiency measures in energy-demand models, we present three case studies showing the DRUMSS framework applied in diverse contexts. For the building sector, a California example demonstrates how right-sizing can reduce embodied energy.

Table 1. Pillars of DRUMSS framework, sectoral examples, and indicators

	Definition	Buildings	Transportation	Industry	Cross-sector
Decentralization (emphasizes where services come from)	receiving energy services/products through a localized rather than distant provider	heat/cool/illuminate only occupied spaces	take public transit instead of personal vehicle	utilize local materials	reduce online shopping
		build with locally available materials	travel locally instead of internationally	on-site self-energy use (e.g., waste heat recovery)	buy local (reduces embodied transport emissions); cook at home
		purchase locally produced home products and appliances	enable consumers to maintain their own vehicles (supply spare parts and repair information)	–	repurpose old belongings instead of buying new
Indicators for decentralization		energy intensity or material intensity	distance traveled per capita	percentage local material purchased/% local energy produced	shipping distance covered per product/per capita
Right-sizing and reduction (emphasizes sizes and service amounts)	adjusting intensity and amount of usage while the product and service remain the same	adjust thermostat to be more moderate	reduce speed on highways for optimal fuel economy	Right-sizing in production (e.g., producing smaller cars, tiny houses)	consume meat less frequently
		purchase right-size appliances	right-sizing car usage regarding passengers and load	reduce bulk/quantity discounts	–
		limit major appliances (e.g., refrigerator) to 1/household	apply load-matching for trucking	–	–
Indicators for right-sizing and reduction		average household temperature (occupied/not occupied); quantity of laundry loads; quantity of new or replaced appliances	percentage occupancy of car and/or truck trips	–	–
Utilization, timing, and longevity (emphasizes the timing and lifespan of services/products)	extending longevity of products and infrastructure through design changes	design buildings having longer lifespans appropriate use and handling of appliances; repair instead of discard	extend the lifespan of cars/batteries, etc.	develop durable, repairable products	store food properly to lengthen lifespan and reduce waste; compost
	service provision remains unchanged, although frequency and intensity of use may be altered	operate buildings or equipment during set times/turn off heating/cooling/lighting when not needed	–	remanufacturing and repurposing	purchase seasonal fruits and vegetables
Indicators for utilization and longevity		lifespan of new buildings	vehicle lifespan	lower appliance replacement rate; increase rate of remanufacturing/repurposing	–

(*Continued on next page*)

②-1.LBNL

Table 1. *Continued*

	Definition	Buildings	Transportation	Industry	Cross-sector
Multifunctionality (emphasizes combining services)	mode of delivering energy services may be altered essential service remains unchanged	design buildings/rooms to be multifunctional	develop infrastructure to provide services for cars, bikes, and pedestrians	develop multifunctional products/furniture	design clothing that is adaptable to various climates/occasions
Indicators for multifunctionality		–	–	lowered material intensity of equipment	–
Substitution (emphasizes how a service is provided)	a radical modification of behavior to reduce energy consumption through mode switching alters the service substitution requires change to be supported by cultural norms	use natural lighting or ventilation instead of electric solutions	walk or bike instead of driving	better design of housing (passive heating/cooling designs)	compact cities
		layer clothing or use a heated blanket	teleworking/virtual meetings and conferences	do not discard returned products	improved walkability
		use a fan instead of AC	–	–	vegetarian diet
		air-dry clothes instead of using a dryer	–	–	–
Indicators for substitution		heating or lighting per capita or per floor area	vehicle energy consumption per distance traveled; total trips or total distance traveled/ capita	–	–
Sharing (emphasizes using over owning)	utilizing service/product to full capacity rather than individual ownership	communal living and work spaces	ride-sharing/shared e-bikes, e-scooters	–	community facilities; shared meals; shared kitchen and appliances
		appliance and tool sharing	carpooling	–	–
Indicators for sharing		m2 per resident, m^2 per office worker	percentage of shared rides/total trips	–	–

AC, air conditioning.
Data adapted from Brischke et al.[23]

②-1.LBNL

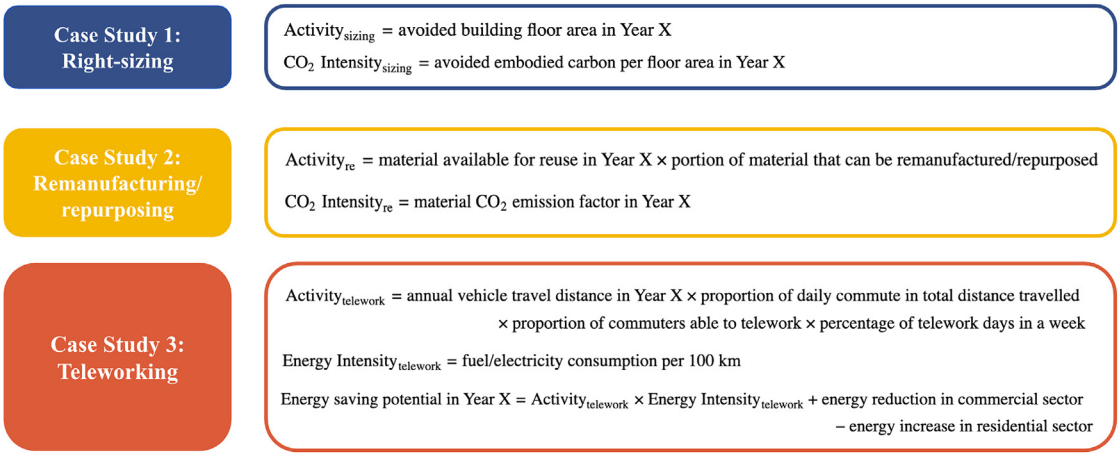


Figure 2. Estimating the climate impacts of sufficiency measures using Kaya identity

For the industrial sector, we estimate potential CO_2 savings from remanufacturing and repurposing scrap steel from end-of-life vehicles in China. For the transport sector, we analyze the mitigation potential of telework in France.

The studies incorporate geographical and sectoral diversity, as well as differences in sufficiency measures. Figure 2 outlines the scope and flow of the modeling exercises using the Kaya identity equation.[25]

As is true for many modeling frameworks, our six DRUMSS components can display interactions and interrelationships. For example, shifting to a plant-based diet could reflect both decentralization (more local produce) and substitution. Operationally, it is important to highlight the dependencies to avoid overcounting, but in practice, some linkages are difficult to quantify. For example, the right-sizing and reduction path could lengthen product longevity, whereas products having multifunctionality might experience greater utilization but potentially lower longevity. More data are needed to better quantify such interactions.

Right-sizing buildings in California

In 2022, nearly 3 in 10 (28.2%) of the sizable US homes (3 bedrooms or more) housed only 1 or 2 older (age 60 years and older in 2024) adults.[26] If 10% of those senior households downsized to 1,000 ft^2 homes (the maximum allowable size for an accessory dwelling unit in California), more than 100 million ft^2 of new construction (only including single-family housing with 3 bedrooms or more) could be avoided,[26] and 11.5 to 13 million tons of CO_2 emissions could be avoided. Using embodied carbon emission factors (tons/ft^2) from C.Scale (https://www.cscale.io/about), we estimated the embodied carbon-saving potential for a typical 2-story single-family home in the San Francisco Bay area and the greater Los Angeles area https://www.cscale.io/aboutas being equivalent to removing 2.5–3 million gasoline-powered passenger vehicles from the road annually. Figure 3 shows the magnitude of these potential savings in comparison to the baseline emissions from new housing construction in 2022. If a similar measure were implemented in regions where cement and steel are the primary building materials, rather than wood as in California, then the embodied carbon would be reduced even further.

Although downsizing may increase well-being—reduced maintenance or a more age-friendly setting—the policy landscape and supply of viable alternatives may make it impossible for individuals to move to a smaller home without incurring increased housing costs.[27] Enacted in 2021, the HOME Act (SB9)[28] removed single-family zoning, enabling the development of up to four housing units on lots previously designated for single-family homes. This policy change has significant potential to increase the supply of "missing middle" housing.

Remanufacturing and repurposing scrap vehicles in China

Developing a circular economy has become a national strategy in China.[29] This includes remanufacturing and repurposing, which extend a product's lifespan (a utilization, timing, and longevity measure) by restoring it or its components to like-new condition or repurposing them into other products or components. Scrap metal can be remanufactured into its original products or repurposed into items ranging from furniture or sculptures to shipping containers or construction materials. Parts unsuitable for those processes can be recycled. Compared to creating new products, the needs for raw material extraction and energy-intensive production are reduced. Although the operational emissions of remanufactured/repurposed products are uncertain, this case study concerns production.

Evidence[30–32] showed that 10% of the scrap steel from vehicles could be remanufactured or repurposed (ie, reused) and 75% recycled. Based on the China DREAM model's deep mitigation scenario,[33] we evaluate CO_2 emission factors for steel production by both blast furnace-basic oxygen furnace and electric arc furnace (EAF) to reflect technological advancements and power sector decarbonization.

As Figure 4 shows, remanufacturing or repurposing steel components from end-of-life vehicles could avoid as much as 106 million tons of cumulative CO_2 equivalent emissions between 2025 and 2050. Steel components unsuitable for remanufacturing could be recycled for EAF production, resulting in even greater savings. Realizing the climate benefits of remanufacturing and repurposing requires better standardization of remanufactured products and more efficient reverse logistics systems.[34]

Teleworking in France

In France, teleworking gained traction among office workers when the COVID-19 pandemic began in 2020. About one-third of jobs in France can be done remotely.[35] French statistics show that an average car travels about 12,000 km/year,[36] with the daily commute to work representing about 25% of this total. Several modeling scenarios recognize telework as a decentralization sufficiency measure.[37–39] One scenario considers a likely teleworking measure as 2.5 days/week for office jobs.[37] If one-third of workers can telework and do so half the time, we estimate that the annual kilometers per car would be reduced about 8%. For an average car consuming 6.8 L/100 km,[40] an annual consumption of 816 L would decline to 750 L (or 7,750 to 7,130 kWh), resulting in 9 million tons of annual CO_2 savings potential (as of 2023, France's fleet of 38.9 million light-duty vehicles emitted an average of 0.239 kg CO_2 per kilometer[38,40]) (see Figure 5).

The reduced energy consumption should be reflected in the commercial sector, but may be partly offset by a rebound effect in the residential sector. For instance, if teleworking is adopted widely, the need for office space should decline, which may reduce energy consumption in commercial buildings, and converting empty offices into residential housing would yield even greater climate benefits.[41] However, if people decide to live farther from the office or to use the time saved from commuting for other trips, we would expect a rebound effect in both transport and housing. The effects would likely depend on local economic and

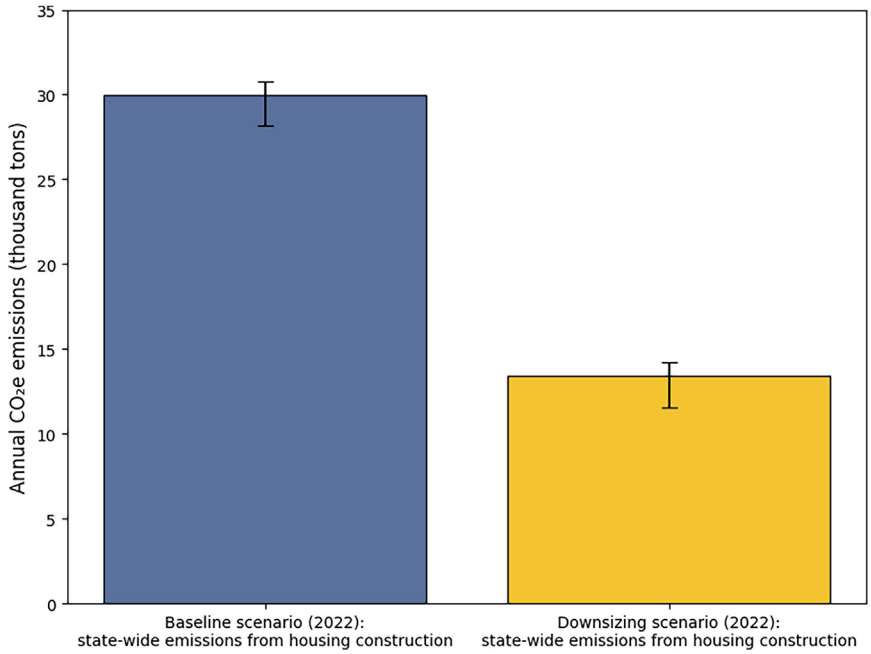


Figure 3. Potential avoided CO_2e emissions from a housing downsizing scenario in California

In the downsizing case study, the baseline scenario estimates the embodied emissions from 10% of large single-family homes (≥3 bedrooms) occupied by "empty nesters." The downsizing scenario, however, highlights the avoided embodied carbon from new construction if these large single-family homes were made available through downsizing measures.

demographic conditions. A review of more than 1,609 studies of the effects of teleworking on travel concluded that telework may lead to longer commutes and more urban sprawl.[42] In Japan, although teleworking saved about 5%–6% in automotive energy consumption, it caused a rebound of about 1%–2% in the building sector in medium and large cities.[43]

This case study demonstrates the uncertainty in estimating the climate impacts of teleworking. Implementing this sufficiency measure requires considering local context. For instance, teleworking may offer the greatest savings in areas where commuting relies heavily on automobiles. Additionally, successful telework implementation requires robust policy support—for example, French labor laws (2017 and 2021) provide explicit legal rights for remote work.[44,45]

ENABLING MECHANISMS

Implementing sufficiency principles embodied in the DRUMSS framework will encounter significant challenges, including a lack of general knowledge about energy used in daily life. Although this knowledge gap applies to operational energy use, it is even more pronounced for the embodied energy of a product or service. People have little awareness of the structural components of consumption, such as how food is produced or waste managed. Sufficiency measures face many of the same economic barriers as energy-efficiency actions. Because accepting sufficiency requires a shift at both an individual and an institutional level from the dominant social paradigm of growth and resource possession, enabling mechanisms must be created. Below are practical actions that policymakers, scientists, and other stakeholders can take to support the implementation of sufficiency measures.

Policymakers

The DRUMSS analysis identifies key policy needs for enabling sufficiency measures. Policymakers should first remove institutional barriers to actions and then develop regulatory mechanisms supporting sufficiency. Policymakers at all levels (national, municipal) can remove conditions that limit sufficiency measures, such as minimum lot area requirements in building codes. As mentioned earlier, California's SB 9 encourages homeowners to build duplexes or subdivide their lots.[46] Policymakers also can emphasize the benefits of these measures, such as housing affordability and cost savings from sharing and right-sizing and reduction.[47] They can establish stringent energy-efficiency standards and building codes that penalize oversized appliances and limit maximum energy consumption regardless of floor area[48] while incentivizing smaller appliances, buildings, or vehicles. Policymakers can also increase public awareness of sufficiency actions through campaigns, demonstrations, and pilot programs.[49]

Fiscal policies can include energy and/or carbon taxes on over-consumption, such as a vehicle miles traveled tax and registration tax based on carbon emissions.[48] Policymakers can incentivize product designs that prioritize durability, utilization, and longevity. Product labels could indicate minimum lifetimes and cost-savings potentials,[49] and funding or tax incentives can support the development of right-sized or multifunctional products. Other incentives include reduced tolls for high-occupancy vehicles,[50] granting priority road access for ride-sharing and carpooling, or enforcing speed limits to support optimal fuel economy. Lastly, local urban planners play an important role in updating infrastructure to accommodate sufficiency actions, such as providing decentralized common spaces (e.g., farmers' markets, parks) and safe pedestrian and bike lanes.

Scientists

Scientists, particularly those involved in modeling energy systems, can leverage the DRUMSS framework and indicators to assess the mitigation effects of sufficiency measures. Research should also evaluate the well-being benefits and socioeconomic impacts of measures. Robust scientific evidence can buttress a compelling narrative for shifting paradigms. Such assessments, useful in policy advising, can be integrated into national or local energy strategies. For instance, in 2022 France established the concept of sufficiency, or "sobriété" in French, as one of four pillars in the national energy strategy. For the building sector, sufficiency involves measures such as setting a maximum temperature of 19°C in offices (right-sizing/reduction), instituting a 15-day delay at the start and end of the heating period (utilization, time/longevity), and reducing the use of domestic hot water in offices (right-sizing/reduction).[51] Although sufficiency has not yet been incorporated into the European Union's policy framework, research projects such as FULFILL,[52] CLEVER,[53] and ENOUGH [54] are informing European

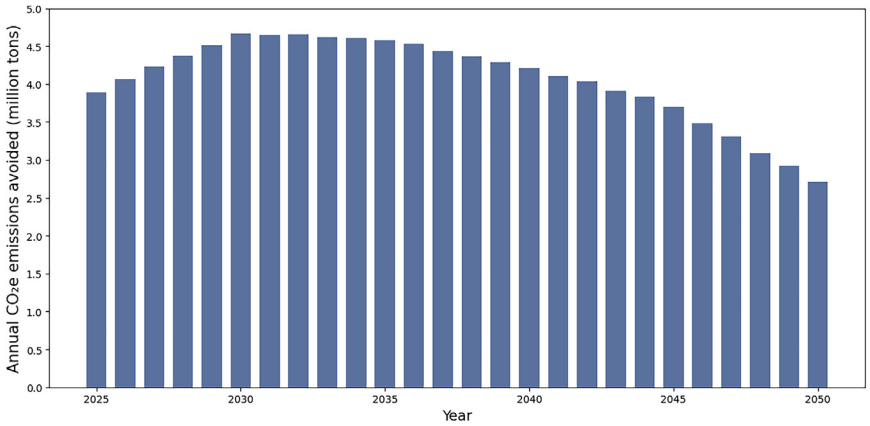


Figure 4. Potential avoided CO_2e emissions from remanufacturing or repurposing scrap vehicles in China
The avoided emissions do not include avoided use of other materials, avoided vehicle emissions, or profits from recycling scrap steel.

policymakers about sufficiency and associated implementation strategies. Technical researchers must collaborate with social scientists and communities to understand the social challenges facing sufficiency measures,[10,55,56] especially because behavioral changes involve inertia and uncertainty.

Other stakeholders

Manufacturers, consumers, and environmental non-governmental organizations (NGOs) also can accelerate the paradigm shift toward sufficiency. Designers, manufacturers, technology developers, and investors can help facilitate sufficiency while seizing resulting business opportunities. Technology developers can create control technologies or Internet-based applications that realize the potential of sufficiency measures. The business community can implement market-based strategies aimed at inducing consumers to moderate consumption.[9,56,57] Strategies could include circular economy models, product-service systems, life cycle thinking, or regional value chains. Adopting such strategies, however, necessitates changing sales tactics and marketing strategies, along with shifting toward mission-driven business models.[9]

NGOs and policymakers can incentivize product designs that prioritize durability. Product labels should indicate minimum lifetimes and potential cost savings[58]; funding or tax incentives can support development of right-sized or multifunctional products. Stakeholders can communicate the importance and value of sufficiency in everyday practices. Consumers and NGOs can create demand for business models that emphasize sufficiency rather than consumption.

Some designers, manufacturers, and technology developers already implement sufficiency principles. Architects, for instance, may adopt a fabric-first approach, prioritizing building designs that enable occupants to minimize energy use without retrofitting the building envelope. Automatic controls and default settings also improve building performance.[23] Buildings that feature multifunctional layouts enable smaller living spaces and, consequently, greater affordability. Repurposing commercial buildings for residential use can address housing shortages while incorporating sufficiency measures.[40]

CONCLUSION

Energy and climate models are vital for informing policymaking during the global transition to carbon neutrality. Unfortunately, sufficiency measures have been largely overlooked in modeling net-zero transitions. We invite researchers to utilize the DRUMSS framework to develop deep decarbonization scenarios that prioritize sufficiency and low energy demand measures. By applying this comprehensive

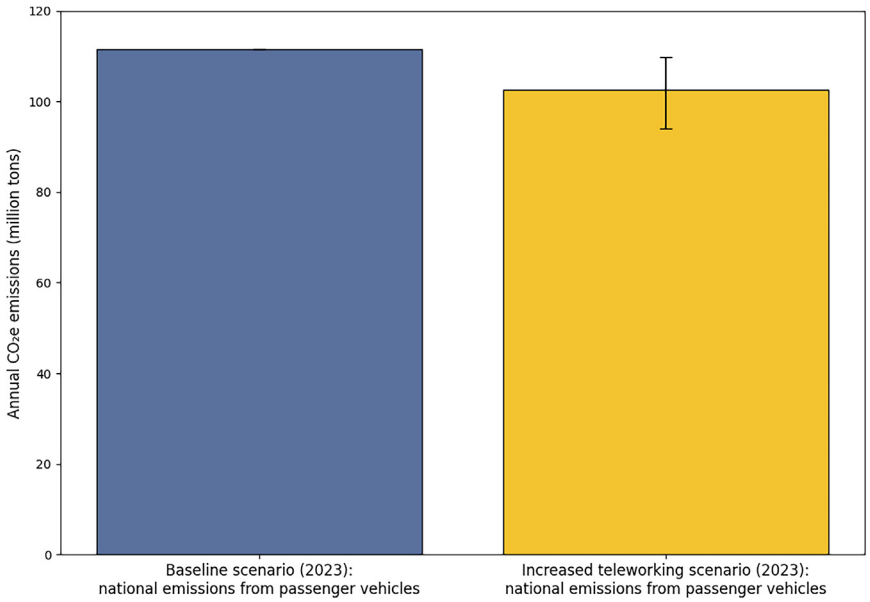


Figure 5. Potential Avoided CO_2e emissions from increased teleworking in France

modeling framework, researchers may identify measures that have been missed but can point out unexplored transition pathways.

The DRUMSS framework encourages interdisciplinary collaboration to augment the indicators and data required to communicate the benefits of sufficiency measures. Those efforts will enable policymakers to establish the necessary technologies and infrastructure and improve the affordability and accessibility of needed lifestyle changes. Future research, including policy experiments and evaluation studies, can test the feasibility of sufficiency in everyday life.

Our three case studies illustrate how the DRUMSS framework can quantify the benefits of sufficiency principles in various locations. It is difficult, however, to quantify sufficiency globally and for regions that lack robust or granular data. Work is needed to quantify sufficiency actions using limited data. Additional research is needed to better understand the interrelation of sufficiency and well-being, as informed by frameworks such as DRUMSS.

As the world grapples with the escalating impacts of climate change, the necessity for sufficiency to promote well-being within ecological limits must be communicated broadly. The framework described herein supports both the scientific study and practical application of energy sufficiency. Interdisciplinary collaborations will be crucial to communicating and implementing sufficiency concepts as we learn how to live within our means while providing widespread well-being.

ACKNOWLEDGMENTS

This work was supported by the Energy Demand Changes Induced by Technological and Social Innovations network, an initiative coordinated by the Research Institute of Innovative Technology for the Earth and the International Institute for Applied Systems Analysis and funded by the Ministry of Economy, Trade, and Industry, Japan. The authors would like to extend our gratitude to Professor Qi Zhang from Northeastern University (China) and to Hongyou Lu and David Fridley from Lawrence Berkeley National Laboratory for their data inputs and validation. This work was authored in part by the Regents of the University of California for the US Department of Energy (DOE) under contract no. DE-AC02-05CH11231. The views expressed in the article do not necessarily represent the views of the DOE or the US government. The US government retains, and the publisher, by accepting the article for publication, acknowledges, that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for US government purposes.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Creutzig, F., Niamir, L., and Bai, X. (2022). Demand-side solutions to climate change mitigation consistent with high levels of well-being. Nat. Clim. Change 12, 36-46. https://doi.org/10.1038/s41558-021-01219-y.

2. Millward-Hopkins, J., Steinberger, J.K., and Rao, N.D. (2020). Providing decent living with minimum energy: A global scenario. Global Environ. Change 65, 102168. https://doi.org/10.1016/j.gloenvcha.2020.102168.

3. van Vuuren, D.P., Stehfest, E., and Gernaat, D.E.H.J. (2018). Alternative pathways to the 1.5C target reduce the need for negative emission technologies. Nat. Clim. Change 8, 391-397. https://doi.org/10.1038/s41558-018-0119-8.

4. Saheb, Y. (2021). Requirements for a Successful COP 26: Commitment, Responsibilities, Trust. https://www.buildingsandcities.org/insights/commentaries/cop26-sufficiency.html.

5. Princen, T. (2003). Principles for sustainability: From cooperation and efficiency to sufficiency. Global Environ. Polit. 3, 33-50. https://doi.org/10.1162/152638003763336374.

6. Subin, Z.M., Lombardi, J., and Muralidharan, R. (2024). US urban land-use reform: a strategy for energy sufficiency. Build. Cities 5, 400-417. https://doi.org/10.5334/bc.434.

7. Tareen, M.U., Meyer, S., and Thiran, P. (2024). Modeling the impact of energy sufficiency on European integrated energy systems. In 37th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems https://hdl.handle.net/2268/321049.

8. Wiese, F., Taillard, N., and Balembois, E. (2024). The key role of sufficiency for low demand-based carbon neutrality and energy security across Europe. Nat. Commun. 15, 9043. https://doi.org/10.1038/s41467-024-53393-0.

9. Jungell-Michelsson, J., and Heikkurinen, P. (2022). Sufficiency: A systematic literature review. Ecol. Econ. 195, 107380. https://doi.org/10.1016/j.ecolecon.2022.107380.

10. Thomas, S., Therma, J., and Brischke, L.-A. (2015). Energy sufficiency policy: an evolution of energy efficiency policy or radically new approaches? In Proceedings of the 2015 ECEEE Summer Study https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2015/1-foundations-of-future-energy-policy/energy-sufficiency-policy-an-evolution-of-energy-efficiency-policy-or-radically-new-approaches/.

11. Waygood, E.O., Sun, Y., and Schmocker, J.-D. (2019). Transport sufficiency: Introduction & case study. Travel Behavior and Society 15, 54-62. https://doi.org/10.1016/j.tbs.2018.12.002.

12. Sorrell, S., Gatersleben, B., and Druckman, A. (2020). The limits of energy sufficiency: A review of the evidence for rebound effects and negative spillovers from behavioural change. Energy Res. Social Sci. 64, 101439. https://doi.org/10.1016/j.erss.2020.101439.

13. Sandberg, M. (2021). Sufficiency transitions: A review of consumption changes for environmental sustainability. J. Clean. Prod. 293, 126097. https://doi.org/10.1016/j.jclepro.2021.126097.

14. Lage, J. (2022). Sufficiency and transformation A semi-systematic literature review of notions of social change in different concepts of sufficiency. Front. Sustain. 3, 954660. https://doi.org/10.3389/frsus.2022.954660.

15. Malik, J., and Hong, T. (2024). Building Energy Sufficiency to Support the Clean Energy Transition: A Review and Perspective. Proc. Sing. Natl. Acad. Sci. 1-13. https://doi.org/10.1142/S2591722622400099.

16. Grubler, A., Wilson, C., and Bento, N. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat. Energy 3, 515-527. https://doi.org/10.1038/s41560-018-0172-6.

17. Kuhnhenn, K., Costa, L., and Mahnke, E. (2020). A societal transformation scenario for staying below 1.5C, 23. https://www.boell.de/en/2020/12/09/societal-transformation-scenario-staying-below-15degc.

18. International Energy Agency (2021). Net zero by 2050 A Roadmap for the Global Energy Sector analysis. https://www.iea.org/reports/net-zero-by-2050.

19. Sugiyama, M., Wilson, C., and Wiedenhofer, D. (2024). High with low: Harnessing the power of demand-side solutions for high wellbeing with low energy and material demand. Joule 8, 1-6. https://doi.org/10.1016/j.joule.2023.12.014.

20. Toulouse, E., Sahakian, M., and Bohnenberger, K. (2019). Energy sufficiency: how can research better help and inform policy-making? European Council for an Energy Efficient Economy, 331-339. https://www.researchgate.net/publication/336414280_Energy_sufficiency_how_can_research_better_help_and_inform_policy-making.

21. Thomas, S., Thema, J., and Brischke, L.-A. (2019). Energy sufficiency policy for residential electricity use and per-capita dwelling size. Energy Efficiency 12, 1123-1149. https://doi.org/10.1007/s12053-018-9727-4.

22. Sachs, W. (1993). Die vier E's: Merkposten für einen maßvollen Wirtschaftsstil. Politische Ökologie 33, 69-71. [in German]. https://nbn-resolving.org/urn:nbn:de:bsz:wup4-opus-668.

23. Brischke, L.-A., Lehmann, F., and Leuser, L. (2015). Energy sufficiency in private households enabled by adequate appliances. In Proceedings of the 2015 ECEEE Summer Study https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2015/7-appliances-product-policy-and-the-ict-supply-chain/energy-sufficiency-in-private-households-enabled-by-adequate-appliances/.

24. Bento, N. (2023). The potential of digital convergence and sharing of consumer goods to improve living conditions and reduce emissions. Environ. Res. Lett. 18, 124014. https://doi.org/10.1088/1748-9326/ad067e.

25. Calwell, C. (2010). Is efficient sufficient? The case for shifting our emphasis in energy specifications to progressive efficiency and sufficiency. Report to the European Council for an Energy Efficient Economy (ECEEE), 27-28. https://www.eceee.org/static/media/uploads/site-2/policy-areas/sufficiency/eceee_Progressive_Efficiency.pdf.

26. California Department of Housing and Community (HCD). Statewide Housing Plan Dashboard. https://www.hcd.ca.gov/planning-and-community-development/housing-open-data-tools/statewide-housing-plan-dashboard.

27. Wamsley, L. (2023). Many baby boomers own homes that are too big. Can they be enticed to sell them? National Public Radio. https://www.npr.org/2024/04/18/1244171720/baby-boomers-large-houses-millennials-homeownership.

28. California Department of Housing and Community (HCD). Senate Bill 9 (Chapter 162, Statutes of 2021). https://www.hcd.ca.gov/sites/default/files/docs/planning-and-community/sb-9-fact-sheet.pdf.

29. Chen, R. (2023). China's Circular Economy Policies: Review and Reflection. Circular Press 4. https://circulareconomy.europa.eu/platform/sites/default/files/2023-08/China%E2%80%99s%20Circular%20Economy%20Policies_%20Review%20and%20Reflection.pdf.

30. Bobba, S., Tecchio, P., and Ardente, F. (2020). Analysing the contribution of automotive remanufacturing to the circularity of materials. Procedia CIRP 90, 67-72. https://doi.org/10.1016/j.procir.2020.02.052.

31. Abdullah, Z.T. (2021). Assessment of end-of-life vehicle recycling: Remanufacturing waste sheet steel into mesh sheet. PLoS One 16, e0261079. https://doi.org/10.1371/journal.pone.0261079.

32. Eurostat (2024). End-of-life vehicle statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=End-of-life_vehicle_statistics#:~:text=In%202022%2C%20the%20reuse%20and,85.0%25%20or%20more%20in%202022.

33. Zhou, N., Khanna, N., and Zhang, J. (2022). China Energy Outlook 2022 (Lawrence Berkeley National Laboratory). https://international.lbl.gov/sites/default/files/2022-04/China%20Energy%20Outlook%202022-full%20report%2004.22.22.pdf.

34. Yuan, X., Liu, M., and Yuan, Q. (2020). Transitioning China to a circular economy through remanufacturing: A comprehensive review of the management institutions and policy system. Resour. Conserv. Recycl. 161, 104920. https://doi.org/10.1016/j.resconrec.2020.104920.

35. Statista (2021). How much of your work can be done remotely, away from your workplace?. https://www.statista.com/statistics/1226527/share-work-can-be-done-remotely-according-people-france-status/.

36. Statista (2019). Average annual passenger car journeys in France from 2004 to 2018, by fuel type. https://www-statista-com.libproxy.berkeley.edu/statistics/1105129/distance-traveled-in-average-by-passenger-car-france/.

37. Réseau de Transport d'Électricité (RTE) (2021). Energy Pathways to 2050. https://assets.rte-france.com/prod/public/2022-01/Energy%20pathways%202050_Key%20results.pdf.

38. The French Agency for Ecological Transition (2024). Futures in transition [in French]. https://www.ademe.fr/en/futures-in-transition/.

39. France Ministry of Ecological Transition (2018). National Low Carbon Strategy Project: The ecological and inclusive transition towards carbon neutrality. https://www.ecologie.gouv.fr/sites/default/files/documents/Projet%20SNBC%20EN.pdf.

40. Statista (2023). Consommation moyenne de carburant d'une voiture particulière en France de 1990 à 2022, selon le type de carburant [in French]. https://fr.statista.com/statistiques/486554/consommation-de-carburant-moyenne-voiture-france/.

41. Gupta, A., Martinez, C., and Nieuwerburgh, S.v. (2023). Converting Brown Offices to Green Apartments (National Bureau of Economic Research). (NBER) Working Paper 31530. http://www.nber.org/papers/w31530.

42. Zhu, P., and Wang, Y. (2024). The travel-related impacts of telecommuting: An active learning-based systematic review. Travel Behaviour and Society 36, 100762. https://doi.org/10.1016/j.tbs.2024.100762.

43. Hayashi, A., Akimoto, K., and Tsurusaki, T. (2024). Impacts of working from home on household energy demand including automobile fuel: an analysis using official statistics of Japan. 2024 EDITS Annual Meeting.

44. Halsey, R. (2024). Remote Work Laws in France: A Comprehensive Overview (RemoFirst). https://www.remofirst.com/post/remote-work-france.

45. Légifrance (2021). Order of April 2, 2021 extending the national interprofessional agreement for the successful implementation of teleworking. https://www.legifrance.gouv.fr/jorf/texte_jo/JORFTEXT000043353723.

46. California Housing Opportunity (2022). More Efficiency [HOME] Act, SB-9. https://planning.saccounty.gov/Pages/SB9_SB10_Information.aspx.

47. Coleman, R. (2018). Are Tiny Houses Useful and Feasible for Addressing the Homelessness Crisis? (University of California, Berkeley report). https://ternercenter.berkeley.edu/research-and-policy/are-tiny-houses-useful-and-feasible-for-addressing-the-homelessness-crisis/.

48. Bertoldi, P. (2022). Policies for energy conservation and sufficiency: Review of existing policies and recommendations for new and effective policies in OECD countries. Energy Build. 264, 112075. https://doi.org/10.1016/j.enbuild.2022.112075.

49. Anderson, D., and Bokhari, S. (2024). Empty Nesters Own Twice As Many Large Homes As Millennials With Kids. Redfin. https://www.redfin.com/news/empty-nesters-own-large-homes/.

50. International Transport Forum (2018). Road Charging and Tolls. https://www.itf-oecd.org/policy/road-charging-and-tolls.

51. Climate Change Laws (2022). Energy sobriety plan. https://climate-laws.org/document/energy-sobriety-plan_c00e.

52. FULFILL: The Project. https://fulfill-sufficiency.eu/the-project/.

53. Collaborative Low Energy Vision for the European Region (2023). The CLEVER scenario. https://clever-energy-scenario.eu/#clever-major-publications.

54. International Network for Sufficiency Research & Policy (2024). ENOUGH. https://enough.owlstown.net.

55. Raworth, K. (2012). A Safe and Just Space for Humanity. Oxfam Discussion Paper. https://www.oxfam.org/en/research/safe-and-just-space-humanity.

56. Mayer, A. (2017). Democratic institutions and the energy intensity of well-being: a cross-national study. Energy Sustain. Soc. 7, 36. https://doi.org/10.1186/s13705-017-0139-7.

57. Bocken, N.M.P., Short, S.W., and Rana, P. (2014). A literature and practice review to develop sustainable business model archetypes. J. Clean. Prod. 65, 42-56. https://doi.org/10.1016/j.jclepro.2013.11.039.

58. Persson, L., Carney Almroth, B.M., and Collins, C.D. (2022). Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. Environ. Sci. Technol. 56, 1510-1521. https://doi.org/10.1021/acs.est.1c04158.

Progress Report for FY24: Demand-Side Databases Description

Prepared by Lawrence Berkeley National Laboratory, January 2025

1. Sufficiency Database

Purpose

We aim to compile and present measures that reduce energy demand, categorized under the DRUMSS framework (Decentralization, Right-sizing & Reduction, Utilization, Timing & Longevity, Multifunctionality, Substitution, Sharing) developed by Zhang et al., 2025.[1] The database provides essential data, including energy reduction potentials, baseline energy usage, material reduction, activity reduction, and other key metrics. This resource will enable future modeling efforts to achieve deep decarbonization and enhance well-being across global regions.

Data scope

Our database covers all end-use sectors including the building, transportation, nutrient, and industry. In addition to this, we also identify key cross-sectoral linkages to more extensively document embodied energy and its reduction potential throughout the lifecycle of a building or product. The case studies in our database cover mainly developed regions across a wide variety of climate zones. We also include various global studies. All types of sufficiency measures, across the six columns of the DRUMSS framework, are identified and described in our database. Our best efforts have gone towards finding the most recent available data for our baselines and energy reduction potentials. This will allow future researchers to apply local CO_2 emission factors to estimate the climate mitigation potential resulting from the adoption of sufficiency measures.

Description of the sufficiency database

The database organizes information under specific columns such as sector, energy use indicator, baseline energy consumption, climate zone, sufficiency measures, and reduction potentials (energy, material, and activity). Energy reduction potentials include both percentage and, where applicable, absolute numbers in terms of annual kWh reduced per capita or household (units for each measure are defined in the database). To complement the energy reduction case studies, we also include information regarding activity-based reductions (e.g., transitioning from centralized AC to electric fans) and material-based reductions (e.g., utilizing a higher proportion of recycled materials in production processes) as they relate to energy demand and consumption. The

[1] https://www.sciencedirect.com/science/article/pii/S2950160125000026?via%3Dihub

sufficiency measures are broadly categorized by their primary end-use sectors, and we also identify cross-sectoral impacts such as reduced embodied energy from material substitutions.

We utilize the DRUMSS sufficiency framework, developed by Zhang et al. (2025), to categorize energy sufficiency measures by the way they alter the delivery and/or consumption of various energy services (e.g., thermal comfort is an energy service provided by heating and cooling in buildings). The following bullet points briefly define each DRUMSS category:

1. Decentralization: receiving energy services/products through a localized rather than distant provider.
2. Right-sizing & Reduction: adjusting intensity & amount of usage while the product and service remain the same.
3. Utilization, Timing, and Longevity: extending longevity of products and infrastructure through design changes.
4. Multifunctionality: mode of delivering energy services may be altered.
5. Substitution: a radical modification of behavior to reduce energy consumption through mode switching.
6. Sharing: utilizing service/product to full capacity rather than emphasizing individual ownership.

Table 1. Description of Sufficiency Database

Column heading	**Description**	**Values**
Sector	Sector that sufficiency measure is primarily *applied* in; e.g., thermostat scheduler is applied in the buildings sector.	Buildings, Transportation, Nutrition, Industry
Cross-sector impact	Identifies if the sufficiency measure has impacts on other sectors through energy or material demand reduction; i.e., substituting an electric clothes dryer with an air drying method not only results in building energy consumption reduction (from avoided usage of a dryer), but also reduction in the embodied energy from industry material usage & manufacturing of clothes dryers.	Buildings, Transportation, Nutrition, Industry
Energy use/indicator	Denotes the specific energy service or indicator that the sufficiency measure has an impact on; e.g., substituting centralized AC with an electric fan has an impact on cooling energy demand.	Examples values from buildings sector: heating, cooling, lighting, etc.
Avg.	Average consumption per capita (or per household, if	Units are in kWh per capita,

consumption per capita (most recent data)	specified) data from most recent year available. Specific to region and/or climate zone. Used as the baseline energy demand value (before implementing a sufficiency measure).	unless other units are substituted.
Source	Source for avg. consumption data.	Link to reference.
Region	Region associated with the sufficiency measure case study.	State/City, Country, Region, Global
Climate zone(s)	Global climate zone associated with the region in which the sufficiency measure case study takes place in (if applicable). Climate zones based on world climate regions. Used to account for variations across baseline energy demands; i.e., a cold-temperate zone will likely have much higher heating energy demand than a hot-arid zone.	Mediterranean-temperate, Cold-temperate, Hot-arid, Temperate, Hot-humid, etc. based on ArcGIS[2] world climate regions.
Sufficiency measure	Sufficiency measures utilized to realize energy demand reductions, categorized through the DRUMSS sufficiency pillars: 1. Decentralization 2. Right-sizing & Reduction 3. Utilization, timing, longevity 4. Multifunctionality 5. Substitution 6. Sharing	See database.
Energy consumption reduction (%)	Energy consumption reduction due to energy sufficiency measure, as a percentage of the baseline.	Units are in % % reduction = (energy demand *reduction*) / (baseline energy demand)
Consumption reduction (kWh/capita/yr)	Energy consumption reduction due to energy sufficiency measure, in absolute numbers.	Units are kWh/capita/year, unless baseline specifies a different unit of measurement (e.g., per household).
Material reduction (%)	Material consumption reduction due to energy sufficiency measure, as a percentage of the baseline. Specific material type and material units should be given	Units are in % % reduction = (material demand *reduction*) /

[2] https://storymaps.arcgis.com/stories/61a5d4e9494f46c2b520a984b2398f3b

	in the baseline column "Avg. consumption per capita (most recent data)."	(baseline material demand)
Activity reduction (%)	Reduction in activity due to energy sufficiency measure, as a percentage of the baseline; e.g., 5% reduction in driving. Change in activity is not synonymous with change in energy consumption, due to the variation in the *way* activities are done; e.g., the activity of driving can be completed in either a truck or compact car, but the energy consumption will be different across vehicles. The measure of activity reduction may not be applicable to all sufficiency measures.	Units are in %
Source	Reference used to generate reduction (energy, material, activity) estimate	Link to reference.
Additional sources	Additional reference used if applicable	Link to reference.

Data highlights

Energy reduction potentials from sufficiency measures gathered in our database, aggregated by the six columns of the DRUMSS framework, are highlighted in Figure 1 and Figure 2 below. Our data visualizations are intended to highlight the variety of sufficiency measures—across sectors, regions, and DRUMSS columns—included in our sufficiency database. Building on the classifications of sufficiency measures, we can begin to map trends in energy reduction potentials present across our database. Figure 1 presents the annual energy reduction potentials, in percentage terms compared to real-world business as usual (BAU) baselines, from selection of energy sufficiency measures. Wherever applicable, baselines are regionally specific (e.g., a case study of energy reduction potentials for buildings in California is applied to a baseline of average household energy demand in California). Figure 2 presents annual energy reduction potentials in absolute terms (kWh per capita) and highlights the relatively large absolute reduction potentials of Right-sizing & Reduction sufficiency measures across all sectors. Presenting measures from our database in both percentage and absolute terms emphasizes the magnitude of their energy reduction potentials compared to each other (other sufficiency measures) and to their BAU baselines (defined in our database).

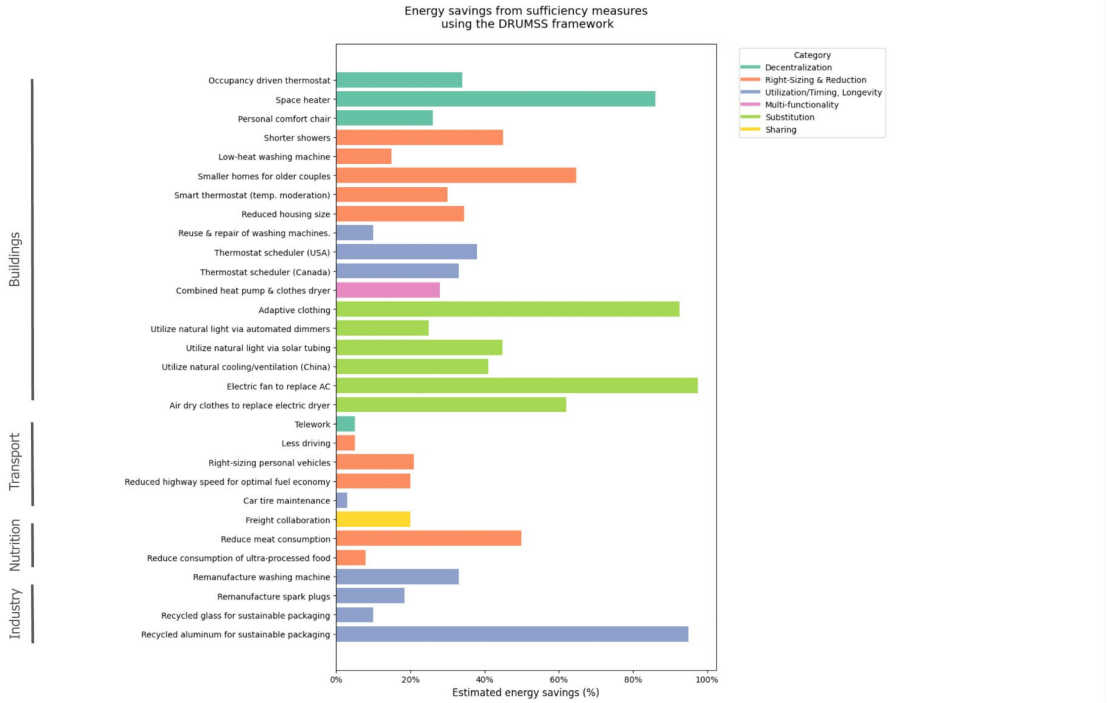


Figure 1. Annual energy saving potentials (%) of sufficiency measures; categorized by the DRUMSS framework.

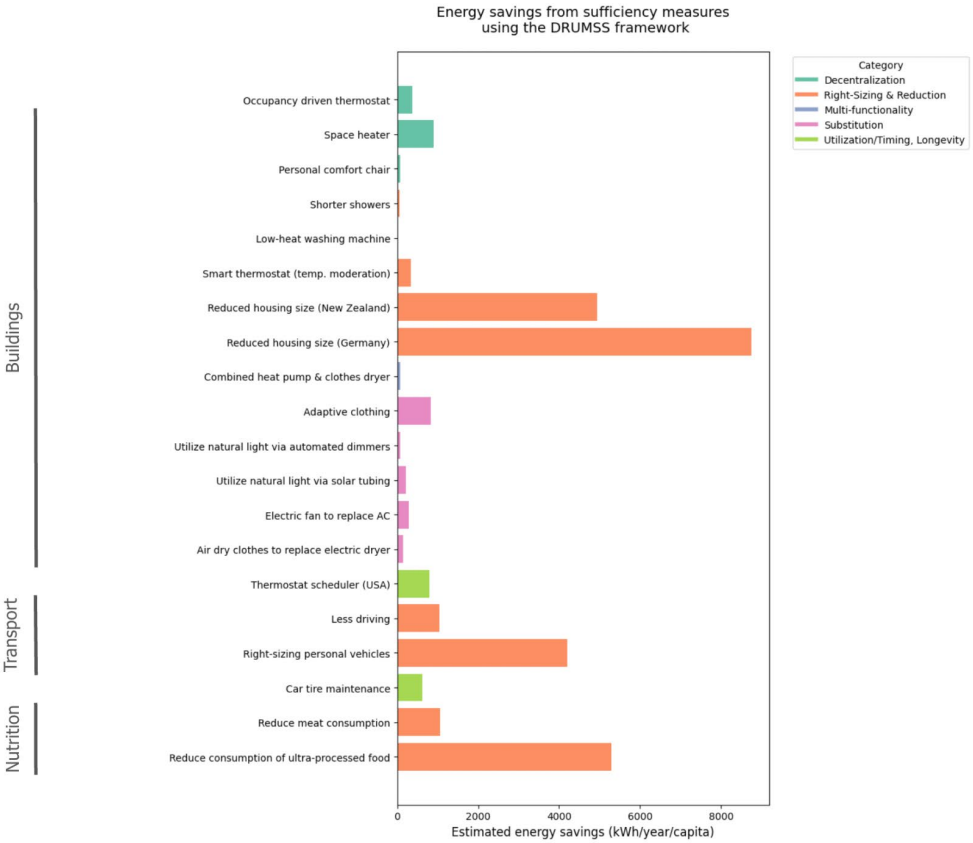


Figure 2. Annual energy saving potentials (kWh/year/capita) of sufficiency measures; categorized by the DRUMSS framework.

Future works

This work identified new indicators and collected extensive sufficiency data across all demand-side sectors. To the best of our knowledge, this is the first database that comprehensively presents sufficiency data using a consistent framework. Across our data collection efforts, we have found a disproportionately large number of case studies on building sector energy sufficiency measures (such as adjustments to living space, heating/cooling demand, water use, etc.) as compared to the other sectors—industry, transportation, and nutrition—that we looked at. Future research could help to fill these information gaps by identifying broader ranges of energy sufficiency measures in these underrepresented sectors by applying sufficiency terminology and concepts to pre-existing measures and by identifying a breadth of cross-sectoral linkages that may not be immediately apparent. For example, it may be helpful in future research to further quantify embodied energy data across both spatial and temporal dimensions, such as analyzing the role of both seasonality and locality in agriculture and food production systems. Throughout our research, we also identified a vast range of qualitative discussions of sufficiency impacts on water use, material and natural resource intensity, and greenhouse gas (GHG) emissions, which have not yet been fully integrated into energy sufficiency modeling and estimates—this can be addressed through future research to more comprehensively identify deep decarbonization potentials and consider the co-benefits of energy sufficiency

2. Global energy demand database

Purpose

Understanding the energy demand driven by services is foundational for estimating and projecting emission trends. Unfortunately, energy service-based drivers are not well understood, and it is currently missing from the latest 6th IPCC Assessment Report (AR) report Chapter 2 - leading to high uncertainties in estimating emission trends. Additionally, demand reduction potential is not fully tapped to realize deep climate mitigation. To fill in this knowledge gap, the Lawrence Berkeley National Laboratory initiated a global energy demand database effort that facilitates the sharing and communication of service-level data. Leveraging the joint works from EDITS researchers, this year, we first focused on the *shelter service* and selected "building floor area" as a proof of concept. This database could potentially inform the 7th IPCC AR report, with a planned focus on service and demand. We also intend to make this database available to EDITS researchers - further enhancing the energy demand research capabilities. In the future, we aim to share a range of service-level data from across the world, regions, and countries and plan to include other service-level data.

Data scope

The demand database currently covers nearly 20,000 historical and projections of total floor area data (ranging between 1970 and 2060) for residential buildings and non-residential buildings at the country level. The definition and scope of non-residential buildings vary by model and study, but generally refer to buildings that are not considered residential buildings. It also includes per capita residential and non-residential building floorspace data, taken directly from original sources or calculated using United Nations population data. The data is sourced from 20 different sources, with contributions mostly from EDITS researchers.

Description of data

The current data collected (see Table 2) provides national and individual-level service demand for buildings and is compatible with the modeling of well-being. The data includes total residential and non-residential building floor area (i.e., building stock) and per capita residential and non-residential floor area. It covers data for historical years that are modeled and calibrated and includes a range of modeling scenarios for the future through at least 2060. The modeling approach varies by data source but includes integrated assessment models, regression models, and scenario-based assessments. We're developing an online dashboard to illustrate this comprehensive data and plan to continue updating them once more data becomes available.

Table 2. Building Floor Area Data Sources

Source	Geographic scope
Fishman, T., N. Heeren, S. Pauliuk, P., *et al*. (2021). "A comprehensive set of global scenarios of housing, mobility, and material efficiency for material cycles and energy systems modelling." *Journal of Industrial Ecology*, Vol. 25(2), 305-320. https://doi.org/10.1111/jiec.13122	Global
Zhang, S., Ma., M., Zhou, N., *et al*. (2024). "Estimation of global building stocks by 2070: Unlocking renovation potential." *Nexus*, Vol. 1(3), 100019. DOI: 10.1016/j.ynexs.2024.100019	Global
Mastrucci, A., van Ruijven, B., Byers, E., *et al*. (2021). "Global scenarios of residential heating and cooling energy demand and CO2 emissions." Climatic Change Vol. 168, 14. https://doi.org/10.1007/s10584-021-03229-3	Global
Deetman, S., Marinova, S., van der Voet, E., *et al*. (2019). "Modelling global material stocks and flows for residential and service sector buildings towards 2050." *Journal of Cleaner Production*, Vol. 245, 118658.	Global

https://doi.org/10.1016/j.jclepro.2019.118658	
Wiese, F., Zell-Ziegler, C., Burghardt, C., *et al.* (2024). "Reducing demand: a quantitative analysis of energy service demand indicators in sufficiency-oriented scenarios." *Environ. Res. Commun.*, Vol. 6, 121003. DOI 10.1088/2515-7620/ad966e	Global
Haberl, H., Baumgart, A., Zeidler, J., *et al*. (2024). "Weighing the global built environment: High-resolution mapping and quantification of material stocks in buildings." *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.13585	Global
Vélez-Henao, J.A., Pauliuk, S. (2025). "Pathways to a net zero building sector in Colombia: Insights from a circular economy perspective." *Resources, Conservation and Recycling*, Vol. 212, 107971. https://doi.org/10.1016/j.resconrec.2024.107971	Colombia
Mastrucci, A., Guo, F., Zhong, X., *et al*. (2024) "Circular strategies for building sector decarbonization in China: a scenario analysis." *Journal of Industrial Ecology*, Vol. 28(5), 1089-1102. https://doi.org/10.1111/jiec.13523	China
Wiese, F., Taillard, N., Balembois, E., *et al*. (2024). "The key role of sufficiency for low demand-based carbon neutrality and energy security across Europe." *Nature Communications*, Vol. 15, 9043. https://doi.org/10.1038/s41467-024-53393-0	Europe
Lu, H., You, K., Feng, W., *et al*. (2024). "Reducing China's building material embodied emissions: Opportunities and challenges to achieve carbon neutrality in building materials." *Iscience*, Vol. 27(3). DOI: 10.1016/j.isci.2024.109028	China
Chatterjee, S., Molnár, G., Kiss, B., *et al*. (2024). "Navigating the transition: Modelling the path for net-zero European building sector." *Renewable and Sustainable Energy Reviews*, Vol. 207, 114827. https://doi.org/10.1016/j.rser.2024.114827	Europe
AR6 Scenario Explorer and Database. International Institute for Applied Systems Analysis (IIASA). https://data.ene.iiasa.ac.at/ar6/#/workspaces	Global
MESSAGEix-GLOBIOM framework. International Institute for Applied Systems Analysis (IIASA). https://docs.messageix.org/projects/global/en/latest/overview/spatial.html	Global
International Energy Agency https://www.iea.org/data-and-statistics/data-product/energy-efficiency-indicators	Global

Data highlights

For residential building floor area, some interesting general trends emerge between developed economies such as the U.S. and rapidly growing economies such as China (Figure 3, Figure 4). For the U.S., total residential floor area has essentially plateaued since the 2000s with very little growth, based on existing models and data sources. In contrast, for China, total residential floor area has grown rapidly and steadily from the mid-1990s through 2020 for most data sources, likely driven by economic growth (and corresponding demand for more per capita floorspace) and population growth. Data discrepancies for the historical years have been observed in both countries and many other countries. The research team plans to look at their assumptions more carefully and conduct additional analysis in the future. For future projections, different models present different scenarios of trends for the residential floor area. For the U.S., most projections show a slowdown in future residential building floor area and plateauing or declining trends through 2060 but a few models projected continued growth through 2060. For China, interestingly, nearly all of the model projections show an expected peak in residential floor area before 2050 with declining total floor area thereafter.

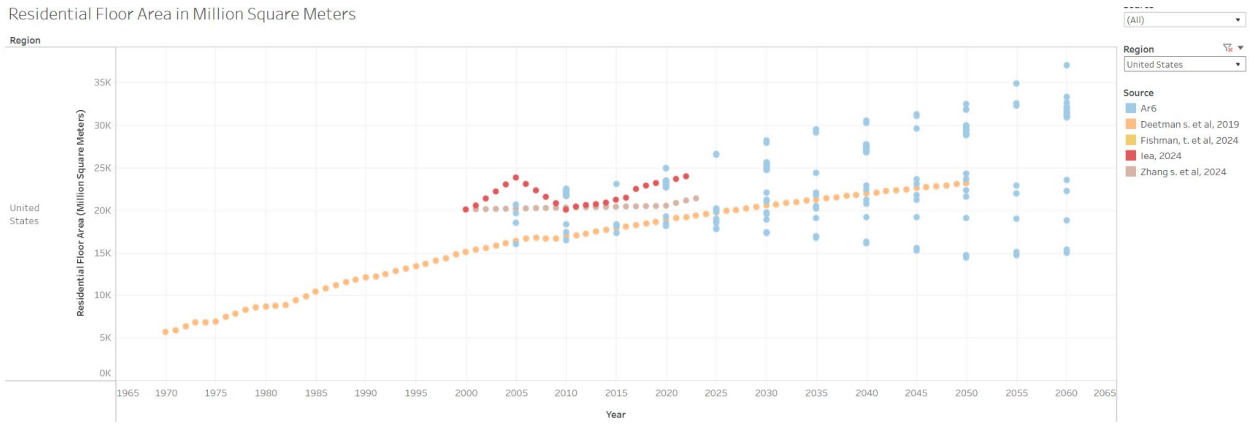


Figure 3. Residential Floor Area Time Series for U.S.

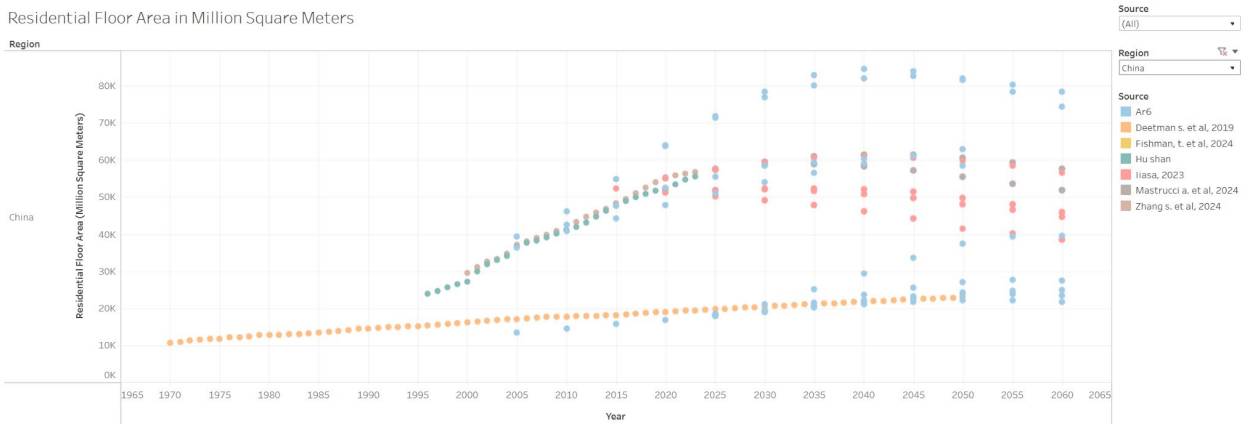


Fig 4. Residential Floor Area Time Series for China

Non-residential building floor area trends in the U.S. and China differ starkly from residential building floor area trends for both earlier years and future projections (Figure 5, Figure 6). For historical trends, existing models and data suggest both the U.S. and China underwent continued linear growth in total non-residential building floor area. For several data sources, China sees a near tripling in total non-residential floor area between 2000 and 2020. For the U.S., there is about 50% growth in total non-residential floor area for the same time period. For future trajectories, all models project continued growth in non-residential floor area in the U.S., albeit at different paces but most of the models project a peak and decline in China's non-residential floor area between 2030 and 2045.

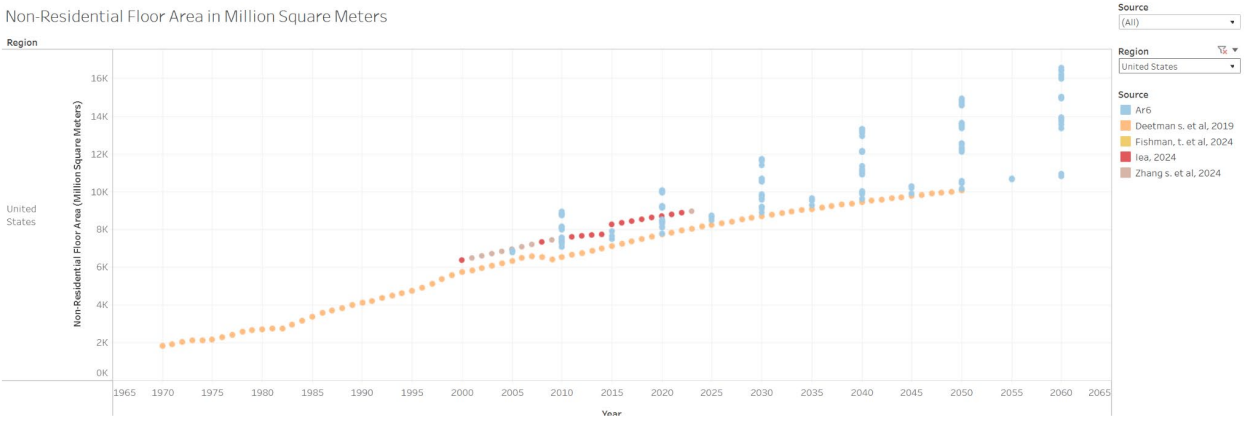


Figure 5. Non-Residential Floor Area Time Series for the U.S.

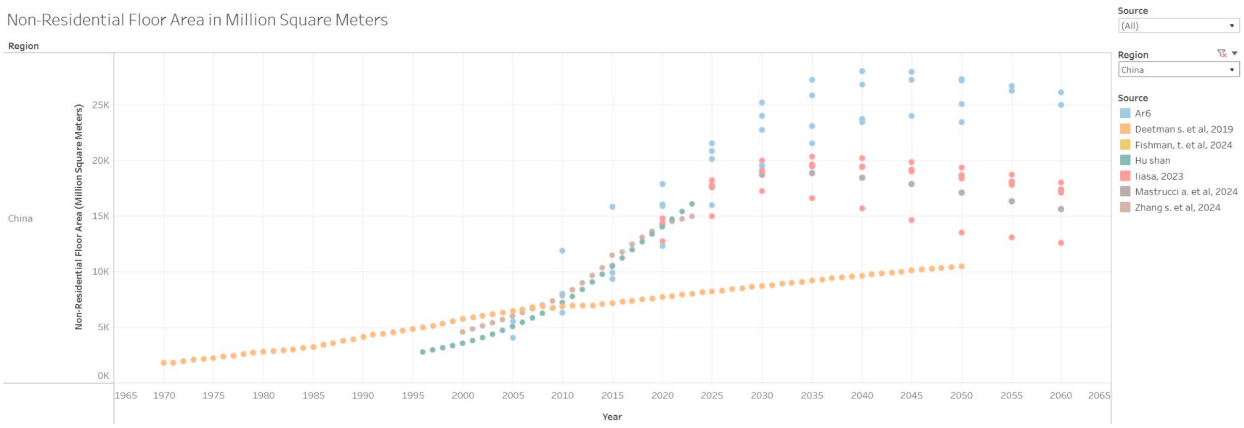


Figure 6. Non-Residential Floor Area Time Series for China

Figures 7 and 8 below compare per capita residential and non-residential building floor area as indicators for comparing different countries' existing levels and future trends. China's per capita residential floor area has increased rapidly since 2000, and is now on par with Germany's earlier level in 2000 and Japan's current level. The current U.S. per capita residential floor area levels are higher than the other selected countries, and there is a greater range of future projections for the U.S. than other countries. For non-residential buildings, growth in the per capita floor area is generally slower for the selected countries with the exception of China.

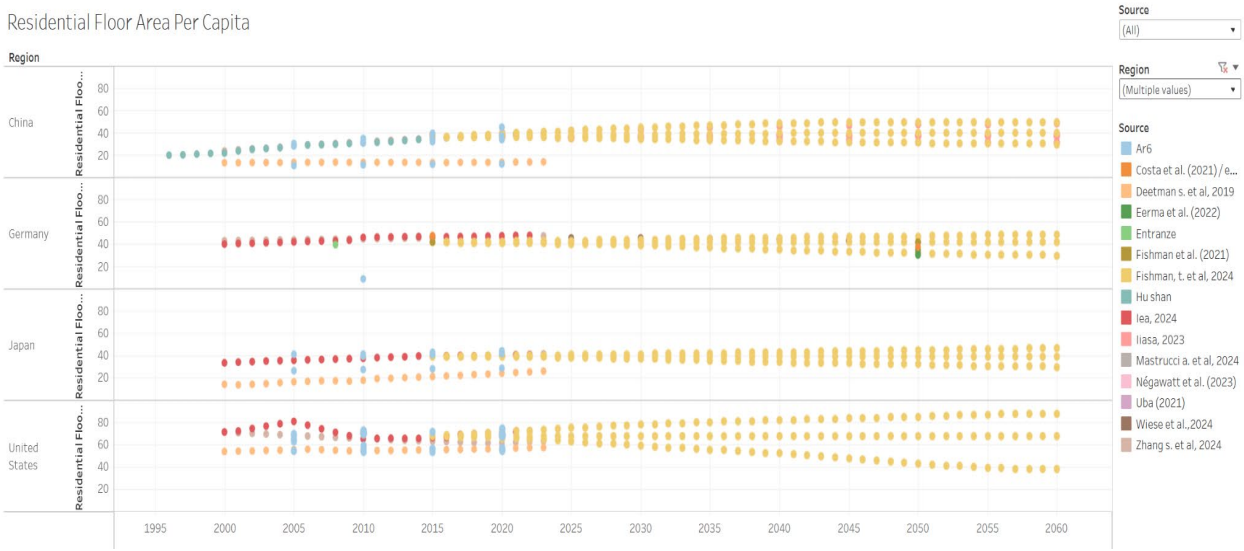


Figure 7. Per Capita Residential Floor Area for Selected Countries

Figure 8. Per Capita Non-Residential Floor Area for Selected Countries

Future work

The global energy demand database uses building sector floor area as a proof of concept, and the residential, non-residential and per capita floor area data series collected illustrate heterogeneity in modeling approaches and subsequent floor area trends. Future work can dig deeper into understanding how different models calculate historical and project future floor area using different drivers and/or algorithms (e.g., population versus economic activity as floor area driver), as well as possible differences in the scope and boundary definitions of non-residential buildings.

In addition, future work can focus on expanding it to include other key energy demand sectors such as transportation and food/nutrition. Additional data sources, including the sufficiency database and other case studies, can also be integrated into the platform to expand the data series and indicators covered for each sector. For transportation and food/nutrition, for instance, potential indicators that could be compatible with existing modeling frameworks include per capita kilometers traveled and per capita meat consumption. Incorporating these sectors and new indicators will help modelers have access to additional data sources and rigorously compare it against other works to inform the modeling of high well-being and low energy demand scenarios. We also plan to synthesize the dataset into an online platform to increase the research visibility of the EDITS data working group.

BOKU Deliverable to EDITS – Financial year 2024/25

Preprint: Small Increases in Socioeconomic Material Stocks Can Secure Decent Living Standards Globally

Preprint: Can the circular economy save the climate? A review of the national to global evidence

Deliverable from the EDITS Industry Working Group and the 2023 fast-track on DLS 11.02.2025

Dominik Wiedenhofer[1] **and Jan Streeck**[1]

[1] .... *University of Natural Resources and Life Sciences, Vienna (BOKU), Department of Economics and Social Sciences, Institute of Social Ecology.*

Acknowledgements: This deliverable reports on work by BOKU for the "Energy Demand Changes Induced by Technological and Social Innovation (EDITS)" project from the financial year 2023/2024, 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 the Ministry of Economy, Trade and Industry (METI), Japan).

Keywords: climate change mitigation; demand-side measures; circular economy; energy; material stocks and flows; emissions; social metabolism; modelling; decent living standards

EDITS
Energy Demand changes Induced by Technological and Social innovations

BOKU

SEC
Institute of Social Ecology

③BOKU

Contents

BOKU Deliverable to EDITS – Financial year 2024/25 1

1) Deliverables for the fiscal year 2024/25 3

2) Preprint: Small Increases in Socioeconomic Material Stocks Can Secure Decent Living Standards Globally..... 4

3) Preprint: Can the circular economy save the climate? A review of the national to global evidence 5

1) Deliverables for the fiscal year 2024/25

In 2024/25 the University of Natural Resources and Life Sciences Vienna (BOKU) led two research contributions within EDITS and contributed to several ongoing efforts from the EDITS consortium. As specified in the contract for the financial year 2024/25, we herein submit the deliverable including the following contents:

- Preprint of the research article "Small Increases in Socioeconomic Material Stocks Can Secure Decent Living Standards Globally" which is under review at the peer-reviewed journal Nature Sustainability (submitted January 2025). The pre-print is freely available and can be published on METIs website. We will share the final publication within EDITS.
- Preprint of the research article "Can the circular economy save the climate? A review of the national to global evidence" which is under review at the peer-reviewed journal *Annual Review of Environment and Resources* (*ARER*) (submitted November 2024). The pre-print is freely available and can be published on METIs website. We will share the final publication within EDITS.
- 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.

<u>In 2024/25, additional contributions to EDITS include the following items:</u>

- Presentation of the paper "Small Increases in Socioeconomic Material Stocks Can Secure Decent Living Standards Globally" at the 15th Conference of the European Society for Ecological Economics & 10th International Degrowth Conference in June 2024, as well as at the EDITS Annual Meeting in October 2024
- Webinar with presentations by Jamie Nieto, Paul Brockway, and Carey King: "New avenues for macro-economic modelling under global constraints: The HARMONEY, MARCO, and MEDEAS models", 16.07.2024 | 9-10:30 a.m. CDT.

2) **Preprint:** Small Increases in Socioeconomic Material Stocks Can Secure Decent Living Standards Globally

Streeck, Jan[1], Veléz-Henao, Johan[2], Kikstra, Jarmo S.[3,4,5], Pachauri, Shonali[3], Min, Jihoon[3], Krausmann, Fridolin[1], Haberl, Helmut[1], Pauliuk, Stefan[2], Zaini, Tommaso[3], Wiedenhofer, Dominik[1]

1 Institute of Social Ecology, BOKU University, Vienna, Austria
2 Industrial Ecology Freiburg, Albert-Ludwigs-University Freiburg, Germany
3 International Institute for Applied Systems Analysis, Laxenburg, Austria
4 Centre for Environmental Policy, Imperial College London, London, United Kingdom
5 The Grantham Institute for Climate Change and the Environment, Imperial College London, London, United Kingdom

Abstract

Global inequalities in resource use leave billions of people below decent living standards (DLS). Achieving universal access to DLS is estimated to only moderately increase energy use and greenhouse gas emissions. Implications for the necessary expansion of socioeconomic material stocks in buildings, infrastructure and machinery remain underexplored. We estimate that closing global DLS gaps would need less than a 12%-increase in already existing material stocks, if stock-building efforts are focused solely on DLS. At current construction rates, this could be accomplished by 2030. However, if historical trends of unequal stock growth driven by demands beyond DLS persist, stock requirements could rise ten times, putting the sustainable development goals (SDGs) at risk. To achieve the SDGs, it is essential to prioritize stock-building for DLS while reconsidering the expansion of stocks for demands beyond DLS, especially in affluent regions. Such a strategy could ensure DLS for all within reasonable resource use limits.

The article is currently under review at *Nature Sustainability* and available as preprint, which you can download here: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5111257

3) **Preprint:** Can the circular economy save the climate? A review of the national to global evidence

Dominik Wiedenhofer[1], Hanspeter Wieland[1], Sina Leipold[2], Chika Aoki-Suzuki[3], Takuma Watari[4], Glenn A. Aguilar-Hernandez[5], Simon Graf[1], Oreane Y. Edelenbosch[6], Marianne Zanon-Zotin[6], Lisa Kaufmann[1], Patricia Fortes[7], Willi Haas[1], Jan Streeck[1]

1 Institute of Social Ecology, BOKU University, Vienna, Austria
2 Helmholtz Centre for Environmental Research, Germany
3 Institute for Global Environmental Strategies, Japan
4 National Institute for Environmental Studies, Japan
5 Institute of Environmental Sciences (CML), Leiden University, Netherlands; Academia de Centroamérica, Costa Rica
6 Utrecht University, The Netherlands
7 NOVA University of Lisbon, Portugal

Abstract

While global resource use and GHG emissions keep increasing, the circular economy (CE) has ascended to the forefront of global policy-, business- and research agendas. Crucially, equating the CE only with recycling is too simple, as it targets the entire lifecycle of products and provisioning systems. Through narrower, slower and more closed material cycles, it aims to avoid waste, primary raw materials and land use, thereby potentially saving energy and mitigate GHG emissions. From 75 national to global level studies combining over 500 detailed measures into narrower-slower-closed CE scenarios, we find an average GHG mitigation potential of 16% [0-85%]. Combined with energy efficiency and decarbonization we find on average mitigation potential of 44% [1-100%]. Most ambitious CE scenarios indicate that stabilizing global resource use at 20% above current levels might be feasible. Future research should use agreed upon frameworks, strengthen the links between industrial ecology and macro-economic modeling and improve upon economy-wide monitoring frameworks, to better capture the CE's potential for climate change mitigation.

The article is currently under review at *Annual Review of Environment And Resources* (ARER) available as preprint, which you can download here:

https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5034599

Title: More benefits with lower demand- Quantifying the co-benefits of energy demand measures in the Residential building sector

Authors: Souran Chatterjee[1], Alessio Mastrucci[2], Jingjing Zhang[3], Michelle Johnson-Wang[3], Pallav Purohit[2], Elena Verdolini[4], Gregor Kiesewetter[2], Benigna Boza-Kiss[2], Shaohui Zhang[2], Nuno Miguel Bento[5], Diána Ürge-Vorsatz[6]

1. University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK
2. IIASA, Schlossplatz 1, Laxenburg, Austria
3. Lawrence Berkeley National Laboratory. 1 Cyclotron Rd, Berkeley, CA 94720
4. Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici via Marco Biagi 5 - 73100 Lecce, Italy
5. ISCTE, Av. das Forças Armadas, 1649-026 Lisboa, Portugal
6. CEU, Quellenstraße 51, 1100 Wien, Austria

Key words: Co-benefits; Residential buildings; Energy Demand; Well-being; Net-zero

Abstract:

Despite the enormous potential, co-benefits often go unnoticed and unmeasured, leading to underinvestment in climate change measures. The lack of quantitative evaluation of these benefits is largely due to an underappreciation of their scale and impact. Moreover, even in cases where co-benefits are quantified, these impacts are often perceived as being relevant only to countries in the Global South. However, studies have demonstrated the potential of climate change measures in both the Global South and the Global North, challenging this notion of exclusivity. Despite this, there remains a lack of evidence quantifying the co-benefits of climate change measures for countries in both regions. Therefore, this research aims to identify, quantify, and monetize co-benefits related to health, energy security, and employment resulting from one specific climate change mitigation measure (Low energy demand measures-LED scenario): high-efficiency building renovation in representative countries in the Global South (e.g., India) and the North (e.g., UK). The findings of our study show that in India, premature mortality under the reference scenario is projected at 1.27 million in 2030 and 1.60 million in 2050. The LED scenario reduces these figures to 1.56 million in 2050, representing decreases of 61,683 deaths, primarily due to building sector strategies such as clean cooking

solutions. Similarly, in the UK, premature mortality in the reference scenario is projected at 23.73 thousand in 2050. Under the LED scenario, these figures decline to 20.89 thousand in 2050, reflecting reductions of 2,841 deaths, largely attributable to clean heating solutions. The economic benefit of health impact could be as high as 1,770 million USD in India and 1,439 million USD in the UK by 2050, using the purchasing power parity factor by 2050. The findings of this study show that the demand-side solutions offer benefits at the user level and, while more limited, also improve fuel impacts. The impact on fuels is larger in India, whereas the economic impacts are more significant in the UK (refer to Table 4). In the UK, the share of fossil fuels in the energy mix improves by 5 percentage points in a LED scenario in 2050 compared to 2020, which is a 1% greater improvement than in the SSP2 scenario. Dependency on imports also decreases as a result of interventions, from 79% in 2020 to 72% in the LED scenario, which is 2% better than in reference scenario.

The analysis reveals that incremental energy efficiency (EE) investments between the SSP2 and LED scenarios are projected to generate substantial employment gains. In the UK, these investments are expected to create over 21 million direct and indirect full-time equivalent (FTE) jobs by 2050. In India, the impact is even more significant, with projections exceeding 53 million formal direct and indirect FTE jobs by 2050. When informal employment is included, this figure could rise to nearly 260 million FTE jobs. Even when comparing demand- and supply-side job impacts, the overall effect remains positive for both countries. These findings underscore the importance of LED in countries across both the Global South and the Global North.

Carbon emissions and cost analysis of the entire hydrogen supply chain for steel industry in China

OU, Xunmin; REN, Lei; LIU, Jianzhe; YANG, Yifang; ZHANG, Qin
Institute of Energy, Environment and Economy, Tsinghua University, Beijing 100084, P. R. China

Abstract: This report aims: (1) conduct a comparative study on the carbon emissions of per ton of steel throughout its lifecycle between hydrogen-steelmaking technology and traditional long process and short process steelmaking technologies; and (2) analyse the production costs of per ton of hydrogen-steelmaking technology. Hydrogen energy is a key deep de-carbonization technology option for steel production. This study aims to provide a reference for the selection of technological routes by conducting a fair comparison with the evaluation of other deep de-carbonization technologies, such as scrap-based electric arc furnace (EAF) steelmaking, under the same research framework. This study updates the direct/indirect GHG emissions and steelmaking costs of blast furnace-basic oxygen furnace (BF-BOF), scrap-based EAF, fossil fuel-based direct reduced iron (DRI), hydrogen steelmaking, and CCS technologies in China. Using the H-DR (part) process can only achieve a 43.4% reduction compared to BF-BOF, while the H-DR (full) process results in GHG emissions comparable to scrap-EAF. The study also discusses the unit abatement costs of hydrogen steelmaking technology compared to other emission reduction technologies. The cost of H-DR (full) is 6,186 RMB/tcs, which is twice that of BF-BOF and 1.3 times that of scrap-EAF. The main conclusions are that green hydrogen steelmaking is expected to achieve near-zero emissions and can complement scrap-based EAF. The abatement costs of pure hydrogen steelmaking are relatively high, but by using partial hydrogen or by-product hydrogen, the abatement costs can be reduced to the level of scrap-based EAF.

Key words: Hydrogen supply chain; hydrogen-based steelmaking; steelmaking costs; emission reduction costs; Greenhouse-gas emissions; China

1. Introduction

Under the "carbon peaking and carbon neutrality" goals, hydrogen energy will become an important component of the energy system. Hydrogen energy is a secondary energy source that is low-carbon, flexible, efficient, and applicable in various scenarios. It is characterized by high combustion heat value, cleanliness, no pollution, and diverse utilization forms, making it a promising and ideal new energy technology[1, 2] . Hydrogen can serve as an energy conversion medium, enabling the transformation and substitution of various energy and material types, including electricity, heat, fossil fuels, and industrial raw materials[3]. Thus, it becomes a crucial

⑤Tsinghua Univ

support technology for enhancing the flexibility of the future energy system, promoting deep electrification of end-use energy, and accommodating variable renewable energy[4, 5]. The practical and large-scale implementation of the hydrogen supply chain(HSC) and end-use applications will help drive the transformation of the energy system, ensure energy supply, stimulate the development of high-tech industries, and reduce greenhouse gas (GHG) and air pollutant emissions, making it an important means to achieve China's "carbon peaking and carbon neutrality" goals.

The steel industry accounts for nearly 10% of global emissions, making de-carbonization technologies crucial. However, current analyses of the maturity and de-carbonization performance of hydrogen-based steelmaking technologies in China are unclear, and the de-carbonization costs are particularly uncertain. The application of hydrogen in the steel sector has gradually attracted the attention of China's academic and industrial communities in the context of "carbon peaking and carbon neutrality." Hydrogen-based steelmaking has four main features that are distinct from its applications in road transport: it is a stationary emission source, uses hydrogen as both a reductant and fuel, competes with direct electrolysis/CCS (CO_2 capture and storage) technologies, and targets investment from steel enterprises. These characteristics make hydrogen steelmaking both representative and unique.

As hydrogen-based steelmaking technology is still in the laboratory stage, only the direct reduction of iron using natural gas(NG)/coal-derived syngas and electric arc furnace steelmaking technologies have achieved mass production. Currently, there is limited research on the techno-economic assessment of hydrogen steelmaking. Using techno-economic evaluation methods, Fischedick et al., Hölling et al., and Bashkar et al. analyzed the energy requirements and system costs of using hydrogen as an indirect electrification option for steelmaking based on simulation data. Their conclusions highlighted the additional costs compared to the mainstream blast furnace-basic oxygen furnace (BF-BOF) steelmaking route and indicated that hydrogen steelmaking is feasible under certain assumptions about future hydrogen costs, carbon prices, and energy system configurations[6,7,8]. Fan et al., through a review of laboratory research and industrial demonstration projects on hydrogen steelmaking, hydrogen injection in BFs, biomass substitution, and steel plant CCS retrofits, compared the marginal abatement costs of various routes. They found that the "hydrogen direct reduction iron(DRI) + renewable electricity-driven electric arc furnace(EAF) steelmaking" technology route has moderate marginal abatement costs (approximately \$240/t CO_2) and is the most mature in terms of full industry chain technology[9] . Weigel et al., using a multi-criteria analysis approach (including economic, safety, ecological, social, and political factors), found that hydrogen steelmaking technology is the most promising route compared to CCS and improvements to BF-BOF technologies [10]. Using experimental and modeling simulation methods, Vogl et al., Kaisa et al., Katharina et al., and Tang et al. simulated the material and energy flows of hydrogen steelmaking and hydrogen injection technologies in BF and conducted GHG emission analyses. Their results indicated that hydrogen steelmaking could achieve significant reductions in emissions when the full-process power emissions are below 532 kg CO_2/MWh, while hydrogen injection in BF could potentially reduce total emissions by 5% at a rate of 120 Nm^3/t hot metal[11-14].

Current research on hydrogen steelmaking focuses on techno-economic evaluations based on reviews and simulation analyses of single processes. There are several limitations in these

⑤Tsinghua Univ

studies, which may lead to: (1) A lack of analysis on the impacts of hydrogen steelmaking across the entire industry chain, both upstream and downstream; (2) The use of insufficiently rational system boundaries, which may lead to an overestimation of the GHG emission responsibility of the ironmaking process and, consequently, an overestimation of the emission reduction benefits of hydrogen steelmaking; (3) Simplification of the HSC, with some studies only considering the energy consumption of hydrogen production or directly using life cycle analysis (LCA) results for vehicle-grade high-purity hydrogen. Additionally, although some studies have used LCA methods to analyze BF-BOF versus scrap-based EAF routes (e.g., Tong et al., Ma et al., Liang et al. [15-17]), and coal and NG-based direct reduction (DR) (e.g., Li et al., Nduagu et al. [18,19]), there is currently no comprehensive LCA research comparing BF-BOF, scrap-based EAF, various fossil fuel-based direct reduction iron, hydrogen steelmaking, and CCS under a unified research framework and system boundaries. For China's large and regionally diverse steel industry, these technology routes may each have advantageous application scenarios.

Existing research on hydrogen itself, including its costs and carbon emissions, and the analysis of de-carbonization costs in the steel sector, has several issues which are expected to be researched in more depth: (1)What are the energy consumption, emissions, and costs of hydrogen-based steelmaking technology compared to competing de-carbonization technologies (such as scrap-based EAF steelmaking and CCS retrofits) and existing mainstream technologies (such as BF-BOF steelmaking)?(2)How can a unified model framework be established to simultaneously cover full life cycle emissions and cost assessments, and achieve a fair comparison of various technologies? How can a sufficiently localized full LCA database be developed, particularly to reflect aspects such as hydrogen storage, transport, refueling, and hydrogen steelmaking, which have not yet undergone extensive engineering practice?

This study will update the full life cycle GHG emissions, and levelized costs of the HSC processes (production, storage, transport, and refueling) in China, using a comprehensive analysis model and database for hydrogen supply and application. It will then assess the CO_2 emissions, and costs of hydrogen in the steel production industry and evaluate traditional technology routes and competing de-carbonization technologies under the same system boundaries and base data to ensure consistency in the evaluation results of the three technology routes. Ultimately, this will allow for a fair comparison of the three technology routes and determine the GHG reduction potential and reduction costs of hydrogen steelmaking.

The innovations of this paper include: (1) Developing a comprehensive model and database for analyzing the full life cycle GHG emissions, and costs of technologies such as scrap-based EAF (with hot metal input), fossil fuel-based DR steelmaking, and BF/plant-wide CCS retrofit, achieving a fair and consistent technology comparison. (2) Providing an in-depth and comprehensive analysis of energy consumption, GHG emissions, and reduction costs.

⑤Tsinghua Univ

2. Methodology

2.1 Virtual steel plant method

The methodology primarily includes the construction of a virtual steel plant and updates to the carbon emissions and cost calculations for the entire HSC. The research boundaries of the virtual steel plant encompass the full "cradle-to-gate" process for mainstream steelmaking technologies and low-carbon emission alternative technologies represented by hydrogen metallurgy. This includes all stages from the extraction/production of raw materials (iron ore, limestone, etc.) and fuels (coal, NG, hydrogen), through ore processing and crude steel production, to the output of standard products from the steel plant.

In terms of functional units, this study uses the production of 1 ton of intermediate product crude steel (t crude steel, tcs) as the functional unit without further breaking down specific product types[20, 21]. The study does not currently include the End-of-Life (EOL) stage in the LCA of the BF-BOF process.

The primary methods of using hydrogen in the steel industry include three types: DRI-steelmaking, BF hydrogen injection, and replacement of fuel gas/protective gas in processes like sintering/rolling. Among these, DRI is the most comprehensive hydrogen metallurgy process and is the main focus of this study. The latter two methods are considered for analyzing hydrogen's role in replacing BF hot blast stove gases and fuel in sintering/rolling stages.

In 2020, global DRI production was 104.4 million tons, with 75.6% produced by gas-based shaft furnaces (SF) designed and built by MIDREX and Energiron. Therefore, aside from the BF-BOF and scrap-based EAF (scrap-EAF) processes, our study focuses on comparing various gas-based DRI technologies[22]. The DRI technology processes include those using hydrogen, NG, by-product coke oven gas (COG), and syngas as main raw materials[23, 24]. Notably, considering the sensitivity of gas-based DRI processes to sulfur content in iron ore and the relatively low quality of domestic iron ore in China, this study considers: (1) Improved DRI processes using top gas as cooling gas, which can relax ore sulfur content requirements; and (2) Improved DRI processes introducing NG in the shaft furnace cooling section for carbon replenishment, which can enhance the mechanical strength of DRI products and reduce fragmentation losses[25].

Additionally, due to its porous physical characteristics, DRI is prone to losses from fragmentation and oxidation during storage and transportation. In practice, DRI is stored and transported in three forms: hot DRI (HDRI), cold DRI (CDRI), and hot briquetted iron (HBI). In this study, unless otherwise specified, HDRI, which has lower energy consumption and losses, is used as the storage and transportation form, and HOTLINK (pneumatic transport, hot charging) technology is used for direct input into the EAF.

The technical elements, technology routes, and major assumptions for this study are complex. On one hand, this aims to cover all mainstream technology choices in steel production, while on the other hand, it employs assumptions that align with practical production conditions. Notably, to clarify the emission reduction potential of each DRI route, it is necessary to reasonably estimate the life cycle GHG emissions for DRI routes and design suitable reference objects for BF-BOF and scrap-EAF routes. Previous studies often used Chinese statistical data

⑤Tsinghua Univ

or specific steel plants for comparison. The former is representative but prone to distortion due to inconsistent accounting boundaries and parameter opacity, while the latter is accurate but lacks representativeness[15,18]. Therefore, this study integrates the advantages of both methods by setting up a virtual steel plant. Specifically, the material inputs and outputs are based on national statistical averages, while the material and energy flows for each stage of the technology routes are estimated using actual steel plant data, technology penetration rates, and empirical formulas, aiming to align with statistical data and reviewed by metallurgical industry experts. This research method has been peer-reviewed[26, 27]. Furthermore, due to the high costs of scrap and electricity and the highly controllable technical characteristics of EAFs in China, existing EAF capacity is often used for producing high-quality or specialty steels. Similarly, given the high future cost of hydrogen and the quality requirements for iron ore in DRI processes, this study assumes that future DRI production will also primarily target high-quality or specialty steels. Correspondingly, the virtual steel plant for the BF-BOF process is also based on data from large, high-quality integrated steel plants in China.

In addition to the four main research objects (BF-BOF, scrap-EAF, fossil fuel-based DRI, and H-DR), this study, based on the practical production conditions in China's steel industry, also considers the following sub-processes:

(1) Scrap-EAF (2020) and scrap-EAF: Due to the high costs of scrap and electricity, increased EAF capacity utilization, product carbon content adjustment, and reduced EAF energy consumption, existing EAF equipment in China tends to use a high proportion of hot metal. Conversely, the theoretically most effective GHG reduction benefit of a scrap-EAF process is rare. Therefore, this study designs the scrap-EAF (2020) route to reflect the impact of hot metal input on GHG emissions and costs in China's EAF production, with parameters estimated using Chinese simulation and experimental results.

(2) Hydrogen-based direct reduction(H-DR) and other hydrogen metallurgy processes: Compared to using hydrogen only in the ironmaking stage, ideal hydrogen metallurgy technology (using hydrogen to replace all raw materials and fuels throughout the steel production process) may involve higher emission reduction costs and technical difficulties. Therefore, in recent years, Chinese steel companies such as Hebei Steel have attempted transitional technology routes like BF hydrogen injection. To discuss the costs and emission reduction benefits of transitional technologies, this study sets up four technology routes: BF hydrogen injection (H_2+BF-BOF), NG-DR with hydrogen improvement (H_2+NG-DR, increasing the proportion of H_2 in syngas), partial H-DR (part, only replacing reductants with hydrogen in the SF, with other heat sources still using NG), and full-process H-DR (full, where hydrogen is used throughout the process). The first three are considered transitional, while H-DR (full) represents the ideal case of using hydrogen as extensively as possible.

In addition to the two main technology routes of scrap steel-EAF and fossil fuel-DR, CCS technology is the most important competing emission reduction technology with hydrogen metallurgy. Since the CO_2 concentration in BF top gas and hot stove flue gas is relatively high and accounts for over 65% of a steel plant’s direct emissions, capturing it is cost-effective and efficient. In contrast, capturing other flue gases from the steel plant is relatively expensive. Therefore, this study categorizes CCS deployment in the steel industry into two types: BF CCS and plant-wide CCS, assuming a capture rate of 90%. The amount captured is estimated based on direct emissions obtained in this study [28].

2.2 GHG emissions and cost estimation of the hydrogen supply chain

The LCA analysis model for energy consumption and GHG emissions of the HSC used in this study is primarily based on a significant expansion of the Tsinghua-LCA model developed by our research group[29-35]. The Tsinghua-LCA model is a localized LCA analysis and calculation platform for vehicle fuels in China. It utilizes an iterative computation method to describe, simulate, and estimate the interactions between major terminal energy sources in China, thereby determining the life cycle energy consumption and emission impact factors of various major terminal energies. Based on this, it conducts LCA studies and comparative analyses of various fuel technology routes. The model primarily considers nine main terminal energies, such as raw coal and crude oil, which account for over 90% of the total terminal energy consumption according to the research team's analysis (excluding heat energy). This includes the main process fuels required for the entire HSC, and the interaction of other terminal energy types with these nine types has no significant impact on the overall research results [29]. This study further develops the Tsinghua-LCA model by continuing its framework, using the iterative computation method to simulate the life cycle performance of terminal energy, with specific details available in previous literature [29-35].

Building on the Tsinghua-LCA framework, this study employs a unique life cycle modeling approach to analyze the production and consumption processes of various energy sources within the HSC. These sources include blast furnace gas, COG, converter gas, producer gas, and other energy carriers like dry air, oxygen, nitrogen, low-pressure steam, high-temperature steam, as well as other carbon-containing and energy-containing raw materials and terminal energies such as coke, coke fines, and liquefied petroleum gas. The study models these processes individually, converting them into their respective terminal energies based on their actual production processes. For the methods used to account for energy consumption and GHG emissions in the HSC, as well as the cost accounting methods for the HSC, please refer to the already published literature [33, 36, 37].

3. Data and key assumptions

3.1 Mainstream technology routes

The data for the BF-BOF route is sourced from large integrated steel plants in China, which include auxiliary coking facilities and captive power plants. The full life cycle inventory (LCI) of inputs and intermediate outputs for each stage is detailed in [27], covering raw materials, energy and energy carriers, intermediate products, as well as residual gases, waste heat, and by-products. The resource and recovery amounts of residual heat, furnace dust, and steel slag are based on relevant Chinese studies[38-42]. Additionally, considering the actual operation of steel enterprises, the iron-containing feedstock input into the BOF includes about 10% scrap steel, sourced from sintering, steel processing, and social scrap. The data are derived

⑤Tsinghua Univ

from actual operational data of steel plant EAF and studies on the impact of hot metal input on EAF power consumption and slag production [27]. Inputting hot metal into EAFs can significantly reduce power consumption[43, 44]. To sum up, the life cycle inventories for BF-BOF, scrap-EAF (2020), and scrap-EAF can be derived from [27, 45].

For the H_2+BF-BOF route, this study is based on production practices and theoretical analyses from Hebei Iron and Steel, Capital Steel, and ThyssenKrupp in Germany. It assumes that up to 150 Nm^3 H_2/t of hot metal can replace 27.9 kg of pulverized coal injection without requiring additional modifications to the BF equipment[45, 46]. Furthermore, based on the steel emission inventory research led by the Climate Change Department of the National Development and Reform Commission, the carbon content of pig iron is assumed to be 4.1%, and that of steel products is 0.243%[47].

3.2 Gas-based shaft furnace route

The basic parameters of the main materials are involved in each DR route, including the composition of the ore entering the furnace, the composition of the reducing gas, and the composition of the DRI produced[48-51]. It is noteworthy that the DRI product generated by technology routes such as H-DR has a lower carbon content, which affects the physical parameters of DRI (such as mechanical strength and density, impacting the reaction efficiency within the shaft furnace), the carbon balance of the raw materials in the Electric Arc Furnace (EAF), and the overall energy consumption of the EAF, ultimately reducing the overall efficiency of the production process. Therefore, this study assumes that technology routes such as COG-DR (Coke Oven Gas-Based Direct Reduction) and H-DR utilize improvements like top gas recycling and the addition of NG in the cooling section of the shaft furnace, as provided by suppliers like MIDREX, to adjust the carbon content of DRI to levels similar to those in the NG-DR route.

The life cycle inventory for the DR routes is based on the operational data from demonstration projects of Coal-DR, NG-DR (MID), and NG-DR (ENE) in regions like Saudi Arabia, India, and parts of China. For COG-DR, H-DR routes, and certain default values for other DR routes (e.g., the amount of slag produced in the electric arc furnace), where actual demonstration project data is lacking, the study supplements this with simulation, laboratory test data, and process modeling based on the benchmark equipment and upstream/downstream parameters of the Coal-DR route[18,19].

The life cycle inventory for the Coal-DR technology route is detailed in [27]. The original intent of Chinese researchers in developing the Coal-DR route was to utilize the majority of non-coking coal resources in China, particularly low-rank coal types like lignite. As a result, the desulfurization and de-benzene processes in this route consume a significant amount of energy and produce numerous by-products. Additionally, to adjust the composition of the reducing gas in the shaft furnace (SF) to ensure production efficiency, the Coal-DR, NG-DR, and COG-DR production processes all include carbon capture systems to handle the top gas, capturing approximately 50% of the CO_2 content. However, since China has yet to establish corresponding carbon sequestration/utilization facilities, this portion of CO_2 emissions is listed separately in [27] as direct emissions.

Due to the lack of mature processes for reducing energy consumption and removing slag, there is no global precedent for using 100% DRI as feedstock in the EAF. Therefore, this study assumes that DRI constitutes 90% of the metallic feed in the EAF.

By surveying global demonstration projects and simulation data, the key parameters for DRI production in the NG-DR, COG-DR, and H-DR routes were obtained, highlighting the main differences compared to the Coal-DR route, as shown in [27].

The main differences lie in raw material consumption, electricity consumption, and CO_2 capture quantities[7,11,18,19,50,52-54]. Overall, the H-DR route exhibits the highest comprehensive energy consumption. This is primarily because the reaction of H_2 with pelletized ore is endothermic. As the proportion of H_2 in the SF reduction gas increases, higher reaction pressure and more external heating are required. Additionally, this study assumes that the NG consumed in the SF for H-DR effectively contributes to the carbon balance of the DRI. In other words, the study neglects the minimal direct GHG emissions that this NG might produce.

3.3 Treatment of waste gas, waste heat, auxiliary materials, and by-products

The full life cycle impacts of auxiliary materials such as bentonite and refractory materials are based on the Gabi database and other models, and have been verified and adjusted according to China's power structure, production technologies, and other databases, especially considering the significant electricity consumption of these auxiliary materials[55,56]. Parameters related to by-product system expansion, including benzene, coal tar, asphalt, limestone, and zinc, are directly sourced from the Gabi database to ensure consistency with the coefficients used in China's EPD and the Life Cycle Assessment methodologies of the World Steel Association[57,58].

3.4 Cost parameters

In this study, the costs of steelmaking raw materials and energy are based on market prices from 2020 [59,60]. For fixed and operational maintenance costs, due to the numerous processes and complex technologies involved in steel production, and the large number of technical equipment and infrastructure required, the components of fixed and operational maintenance costs are diverse and vary significantly between steel plants. Comparing cost data from specific steel plants with project pre-feasibility costs provided by DRI suppliers may introduce additional errors due to the ambiguous system boundaries of these two types of data.

Therefore, this study simplifies the approach by using the statistical average values of fixed costs and wage costs from large-scale steel plants in the "China Steel Yearbook 2020" to set the relevant costs for the BF-BOF and scrap-EAF routes. The costs for DR gas-based shaft furnaces are referenced from the simplified methods used in the IEA's comprehensive model, with the fixed cost ratio of DRI-EAF to BF-BOF as a reference.

4. Results and discussion

4.1 Life cycle carbon emission of different processes of steel production

The GHG emissions of conventional steelmaking technologies (blast furnace-converter, blast furnace-converter hydrogenated, scrap/iron electric arc furnace, pure scrap electric arc furnace), hydrogenated/pure hydrogen DRI technologies and fossil fuel DRI that can be used as a transition technology (COG-based DRI, coal-based DRI, NG-DRI designed by MIDREX, NG-DRI designed by Energiron) technologies as transition technologies were analysed for GHG emissions.

The hydrogenation/pure hydrogen direct reduction iron technology is subdivided into three technology subcategories: all-hydrogen smelting (using hydrogen as reductant and fuel), partial hydrogen smelting (using hydrogen as reductant only), and NG-DRI hydrogenation.

The results of the whole life cycle analysis show that the main greenhouse gases (containing CO_2, N2O and CH4) emitted by the pure hydrogen DRI route are comparable to the current scrap-electric arc furnace route, and that DRI as an intermediate product has the potential to be inter-substituted with scrap in electric furnaces. However, if the required reaction heat for the pure hydrogen DRI route is supplied by fossil fuels, the full life cycle carbon emissions of this route are similar to those of the fossil fuel DRI route.

Similar to the ref. [27], under current technological conditions, promoting scrap recycling and expanding EAF capacity can achieve up to about 62.1% GHG reduction. However, due to the underdeveloped scrap recycling industry, high scrap and electricity prices, most EAF plants in China choose to use molten iron to maintain profitability. As a result, the GHG emissions of scrap-EAF (2020) is only 23.3% lower than BF-BOF, which falls short of the ideal reduction effect. This indicates that the construction of EAF capacity in China's steel industry is ahead of the development of scrap collection and processing, necessitating adjustments based on the distribution of scrap resources and existing EAF capacity.

For the fossil fuel-DR technology route, coal-DR's main application value lies in its use of non-coking coal instead of coking coal, aligning well with China's resource endowment. However, its GHG emissions is 11.0% higher than scrap-EAF (2020), making it unsuitable as a primary technology for medium- to long-term GHG reduction on its own. It needs to be combined with CCS. It is worthy to clarify the system boundaries when the CO2 issue is discussed for this industry.

In hydrogen metallurgy, under more ideal HSC conditions, the GHG emissions for BF with hydrogen (H_2+BF-BOF) are 2152.0 $kgCO_2$,eq/tcs [27], representing a 12% reduction compared to BF-BOF. As it does not require additional technological modifications, H_2+BF-BOF is the most cost-effective hydrogen metallurgy technology and can serve as an alternative for GHG reduction in BF-BOF processes besides CCS modifications. It can also be a transitional technology for hydrogen storage and hydrogen technology development in steel plants. However, H_2+NG-DR does not offer significant additional reduction benefits compared to NG-DR (about 3-5%) and requires additional hydrogen supply systems for the shaft furnace,

⑤Tsinghua Univ

which impacts its cost-effectiveness. To avoid high reduction costs associated with "burning hydrogen," the H-DR (part) route, which uses NG for heating in processes such as block production, DRI production, and rolling, has GHG emissions of an about 40% reduction compared to BF-BOF and performs better than COG-DR and scrap-EAF (2020). It can be considered a near-to-medium-term development goal for hydrogen metallurgy technologies.

Although the ideal full-hydrogen route, H-DR (full), involves additional electricity consumption and generates more steel slag, H-DR (full) emissions are still comparable to scrap-EAF, with a lower proportion of direct emissions. In other words, H-DR (full) can be a viable technology choice for achieving ultra-low GHG emissions in the Chinese steel sector under "peak carbon and carbon neutrality" goals, alongside scrap-EAF.

4.2 Steelmaking cost analysis

The costs of various steelmaking technology routes can be seen that the cost of scrap-EAF is 1.54 times that of BF-BOF. In terms of cost composition, the energy and consumables costs of scrap-EAF are lower than those of BF-BOF. Currently, the high scrap prices in China are the main factor leading to the higher cost of scrap-EAF. Moreover, considering that the cost of scrap-EAF exceeds the market price of primary steel products, the current use of molten iron (scrap-EAF (2020)) does indeed significantly reduce costs.

Among fossil fuel-DR technology routes, coal-DR and COG-DR routes have production costs comparable to scrap-EAF (2020), slightly lower than the market price of primary steel products. In the absence of current technological conditions and corresponding incentive policies, both can be considered as technical options for DRI demonstration projects in steel mills.

The cost of H-DR (full) is 6,186 yuan/tcs, which is twice that of BF-BOF and 1.3 times that of scrap-EAF. Without policy incentives, steel enterprises find it difficult to bear the cost of using H-DR (full) for deep GHG reduction. By introducing NG as the fuel for the entire steelmaking process, the cost of H-DR (part) can be reduced to a level comparable to scrap-EAF. In other words, under current technical conditions, the cost of DRI produced by H-DR (part) can serve as an alternative to scrap. The future reduction in the cost of the HSC is expected to further decrease the cost of H-DR, ultimately placing it between BF-BOF and scrap-EAF. At that point, the costs of scrap and high-quality imported iron ore will become the decisive factors affecting the priority of H-DR and scrap-EAF technologies.

4.3 Unit reduction cost analysis and comparison

Further analysis provides the unit GHG reduction costs of various steelmaking technologies compared to the BF-BOF route.

Under current technological conditions, the unit reduction cost for using wind and solar power to produce hydrogen for steelmaking is 2.30 RMB/kg$CO_{2,eq}$. The reduction cost for H-DR (full) is 1.87 times higher than that for scrap-EAF (1.23 RMB/kg$CO_{2,eq}$), and the introduction of NG in H-DR (part) provides only limited improvement in the unit reduction cost.

With future technological advancements and changes in the energy structure, the unit reduction costs for scrap-EAF and fossil fuel-DR are expected to rise. In contrast, the unit reduction cost of H-DR technology is anticipated to fall below 1 RMB/kg$CO_{2,eq}$, approaching

the cost of full-scale CCS technology for the BF-BOF process, making it a significant complement to CCS technology.

In other words, for steel plants located in suitable geographical areas with mature large-scale CCS technology, the unit reduction cost of CCS technology modification is relatively low and only slightly higher than COG by-product hydrogen steelmaking, making it a priority for development. For steel plants without CCS construction conditions or those close to areas with concentrated renewable energy resources, a sliding subsidy of 20-5 RMB/kg H_2 can quickly make hydrogen steelmaking technology cost-competitive compared to EAF, enabling earlier deployment.

5. Concluding remarks

In the steel sector, the GHG emissions of green hydrogen-based steelmaking technology are comparable to those of scrap steel-EAF (Electric Arc Furnace). Both technologies are expected to achieve ultra-low GHG emissions in the future. Currently, the cost of hydrogen-based steelmaking technology using partial hydrogen is comparable to that of scrap steel-EAF. With certain policy support, it could be worth attempting deployment.

(1) Under an ideal HSC, the H_2+BF-BOF route can achieve an about 10% reduction, representing another reduction technology option besides CCS (Carbon Capture and Storage). H-DR (Hydrogen-DR) requires higher reaction heat, so using the H-DR (part) process can only achieve an about 40% reduction compared to BF-BOF, while the H-DR (full) process results in GHG emissions comparable to scrap-EAF. With the de-carbonization of China's electricity, both scrap-EAF and H-DR (full) could further reduce emissions in the future, making them complementary near-zero emission steelmaking technologies.

(2) The cost of H-DR (full) is 6,186 RMB/tcs, which is twice that of BF-BOF and 1.3 times that of scrap-EAF. Without policy incentives, steel companies would find it challenging to bear the cost of deep GHG reductions using H-DR (full). By introducing NG as the fuel throughout the steelmaking process, the cost of H-DR (part) can be reduced to a level comparable to scrap-EAF. In other words, under current technology conditions, DRI produced by the H-DR (part) route can serve as a substitute for scrap steel. Future reductions in the cost of the HSC could further lower the cost of H-DR, positioning it between BF-BOF and scrap-EAF. At that point, changes in the cost of scrap steel and high-quality imported iron ore will become decisive factors affecting the priority of H-DR and scrap-EAF technologies.

(3) Apart from COG-DR, the unit reduction costs of fossil fuel-DR and H-DR technologies are higher than the CCS retrofitting cost for BF-BOF. Future unit reduction costs for H-DR technology are expected to fall below 1 RMB/kg$CO_{2,eq}$, approaching the cost of full-scale CCS retrofitting for BF-BOF. This makes H-DR a significant supplement to CCS technology. For steel mills that do not have CCS construction conditions or are located near areas with concentrated renewable energy resources, a tiered subsidy of 20-50 RMB/kg H_2 can help hydrogen steelmaking technology achieve cost competitiveness compared to EAF, facilitating earlier deployment.

Reference

[1] Mao Zongqiang. Hydrogen Energy: The Green Energy of the 21st Century. Chemical Industry Press, 2005 (in Chinese).
[2] Abe J O, Popoola A, Ajenifuja E, et al. Hydrogen energy, economy and storage: Review and recommendation. International journal of hydrogen energy. 2019, 44(29): 15072-15086.
[3] Yu Guangxin, Ji Qinhong, Liu Qiang, et al. "Analysis and Reflection on the Bottlenecks of the Hydrogen Energy and Fuel Cell Industry." Modern Chemical Industry, 2021, 41(4): 1-4, 10.
[4] Yu Hongmei, Yi Baolian. "Electrolytic Hydrogen Production and Hydrogen Storage." China Engineering Science, 2018, 20(3): 58-65 (in Chinese).
[5] Project Comprehensive Report Writing Team. "Comprehensive Report on China's Long-term Low-carbon Development Strategy and Transformation Pathways." China Population, Resources and Environment, 2020, 30(11): 1-25 (in Chinese).
[6] Fischedick M, Marzinkowski J, Winzer P, et al. Techno-economic evaluation of innovative steel production technologies. Journal of Cleaner Production. 2014, 84: 563-580.
[7] Bhaskar A, Assadi M, Nikpey Somehsaraei H. Decarbonization of the iron and steel industry with direct reduction of iron ore with green hydrogen. Energies. 2020, 13(3): 758.
[8] Hölling M, Weng M, Gellert S. Bewertung der Herstellung von Eisenschwamm unter Verwendung von Wasserstoff. Stahl und Eisen. 2017, 137(6): 47-53.
[9] Fan Z, Friedmann S J. Low-carbon production of iron and steel: Technology options, economic assessment, and policy. Joule. 2021, 5(4): 829-862.
[10] Weigel M, Fischedick M, Marzinkowski J, et al. Multicriteria analysis of primary steelmaking technologies. Journal of Cleaner Production. 2016, 112: 1064-1076.
[11] Vogl V, Åhman M, Nilsson L J. Assessment of hydrogen direct reduction for fossil-free steelmaking. Journal of Cleaner Production. 2018, 203: 736-745.
[12] Tang J, Chu M, Li F, et al. Mathematical simulation and life cycle assessment of blast furnace operation with hydrogen injection under constant pulverized coal injection. Journal of Cleaner Production. 2021, 278: 123191.
[13] Huitu K, Helle M, Helle H, et al. Optimization of Midrex Direct Reduced Iron Use in Ore-Based Steelmaking. steel research international. 2015, 86(5): 456-465.
[14] Rechberger K, Spanlang A, Sasiain Conde A, et al. Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking. steel research international. 2020, 91(11): 2000110.
[15] Liang T, Wang S, Lu C, et al. Environmental impact evaluation of an iron and steel plant in China: Normalized data and direct/indirect contribution. Journal of Cleaner Production. 2020, 264: 121697.
[16] Ma X, Ye L, Qi C, et al. Life cycle assessment and water footprint evaluation of crude steel production: A case study in China. Journal of Environmental Management. 2018, 224: 10-18.
[17] Tong Y, Cai J, Zhang Q, et al. Life cycle water use and wastewater discharge of steel production based on material-energy-water flows: A case study in China. Journal of Cleaner Production. 2019, 241: 118410.
[18] Li F, Chu M, Tang J, et al. Life cycle assessment of the coal gasification-shaft furnace-electric furnace steel production process. Journal of Cleaner Production. 2021, 287: 125075.

[19] Nduagu E I, Yadav D, Bhardwaj N, et al. Comparative life cycle assessment of natural gas and coal-based directly reduced iron (DRI) production: A case study for India. Journal of Cleaner Production. 2022, 347: 131196.
[20] Commission Implementing Regulation (EU) 2021/447 of 12 March 2021 determining revised benchmark values for free allocation of emission allowances for the period from 2021 to 2025 pursuant to Article 10a(2) of Directive 2003/87/EC of the European Parliament and of the Council (Text with EEA relevance).Official Journal of the European Union, 12.03.2021, OJ L 87, 15.3.2021, p. 29–34. https://eur-lex.europa.eu/eli/reg_impl/2021/447.
[21] Commission Delegated Regulation (EU) 2019/331 of 19 December 2018 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council (Text with EEA relevance.). Official Journal of the European Union, 19.12.2018, OJ L 59, 27.2.2019, p. 8–69. http://data.europa.eu/eli/reg_del/2019/331/oj.
[22] MIDREX, World steel dynamics. World direct reduction statistics 2020. https://www.midrex.com/wp-content/uploads/Midrex-STATSbookprint-2020.Final_.pdf.
[23] Millner R, Ofner H, Boehm C, et al. Future of direct reduction in Europe-Medium and long-term perspective. European steel technology and application days. 2017: 26-29.
[24] Chevrier V. Ultra-low CO2 ironmaking. Steel Times International. 2020, 44(7): 29-34.
[25] Arandas M, Chevrier V, Ravenscroft C. New Technologies for Maximizing Operational Flexibility of MIDREX® DRI Plants: Adjusting Product Carbon in MIDREX® DRI Products. AISTECH. 2017, 2017: 979-984.
[26] Ren L, Zhou S, Peng T, et al. A review of CO2 emissions reduction technologies and low-carbon development in the iron and steel industry focusing on China. Renewable and Sustainable Energy Reviews. 2021, 143: 110846.
[27] Ren L, Zhou S, Ou X. The carbon reduction potential of hydrogen in the low carbon transition of the iron and steel industry: The case of China. Renewable and Sustainable Energy Reviews. 2023, 171
[28] Wei Y-M, Kang J-N, Liu L-C, et al. A proposed global layout of carbon capture and storage in line with a 2 C climate target. Nature Climate Change. 2021, 11(2): 112-118.
[29] Ou X, Zhang X, Chang S. Alternative fuel buses currently in use in China: Life-cycle fossil energy use, GHG emissions and policy recommendations. Energy Policy. 2010, 38(1): 406-418.
[30] Li X, Ou X, Zhang X, et al. Life-cycle fossil energy consumption and greenhouse gas emission intensity of dominant secondary energy pathways of China in 2010. Energy. 2013, 50: 15-23.
[31] Ou X, Xiaoyu Y, Zhang X. Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China. Applied Energy. 2011, 88(1): 289-297.
[32] Ou X, Yan X, Zhang X, et al. Life-cycle analysis on energy consumption and GHG emission intensities of alternative vehicle fuels in China. Applied Energy. 2012, 90(1): 218-224.
[33] Ren L, Zhou S, Ou X. Life-cycle energy consumption and greenhouse-gas emissions of hydrogen supply chains for fuel-cell vehicles in China. Energy. 2020, 209: 118482.
[34] Peng T, Ou X, Yan X, et al. Life-cycle analysis of energy consumption and GHG emissions of aluminium production in China. Energy Procedia. 2019, 158: 3937-3943.

[35] Peng T, Ou X, Yan X. Development and application of an electric vehicles life-cycle energy consumption and greenhouse gas emissions analysis model. Chemical Engineering Research and Design. 2018, 131: 699-708.
[36] Wang Minghua, Chen Zeyu, Wang Wen, Ren Lei, Liu Jianzhe, Ou Xunmin. "Carbon Footprint Analysis of the Full Industry Chain of Ammonia Energy Production, Storage, and Utilization in China for Different Application Scenarios." Clean Coal Technology: 2024, 30(5): 1-12 (in Chinese).
[37] Wang Minghua, Wang Wen, Chen Zeyu, Liu Jianzhe, Ou Xunmin, Ren Lei. "Total Cost of Ownership Analysis for Hydrogen Fuel Cell Heavy-Duty Trucks in China." Journal of Automotive Safety and Energy: 2023, 14(6):762-773 (in Chinese).
[38] Zhou Jicheng L X, Shangguan Fangqin, Deng yi, Zhang Chunxia. Energy conversion mechanism and energy efficiency of steel manufacturing process. Iron and steel. 2019, 54(04): 73-82.
[39] Na H, Sun J, Qiu Z, et al. A novel evaluation method for energy efficiency of process industry — A case study of typical iron and steel manufacturing process. Energy. 2021, 233: 121081.
[40] Sun Y, Wang H, Liu L, et al. Solid wastes utilization in the iron and steel industry in China: towards sustainability. Mineral Processing and Extractive Metallurgy. 2017, 126(1-2): 41-46.
[41] Wang J S, Li Y, Feng H X, et al. Progress in treating difficult-to-handle dust and sludge and full-scale resource utilization in an iron and steel industry cluster. Gongcheng Kexue Xuebao/Chinese Journal of Engineering. 2021, 43(12): 1737-1749.
[42] Guo Y, Qie J, Zhang C, et al. Material flow analysis of zinc during the manufacturing process in integrated steel mills in China. Journal of Industrial Ecology. 2021, 25(4): 1009-1020.
[43] Yang L Z, Jiang T, Li G H, et al. Discussion of Carbon Emissions for Charging Hot Metal in EAF Steelmaking Process. High Temperature Materials and Processes. 2017, 36(6): 615-621.
[44] Lee B, Ryu J W, Sohn I. Effect of hot metal utilization on the steelmaking process parameters in the electric arc furnace. Steel Research International. 2015, 86(3): 302-309.
[45] Wang Guang W J-s, Zuo Haibin, Xue Qingguo. Effect of blast furnace gas recycling with hydrogen injection on low carbon development of Chinese ironmaking. China Metallurgy. 2019, 29: 1-6.
[46] Yilmaz C, Wendelstorf J, Turek T. Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions. Journal of Cleaner Production. 2017, 154: 488-501.
[47] Cai Bofeng. City's Greenhouse Gas (GHG) Emission Inventory Research. Beijing: Chemical Industry Press, 2009 (in Chinese).
[48] Sarkar S, Bhattacharya R, Roy G G, et al. Modeling MIDREX Based Process Configurations for Energy and Emission Analysis. steel research international. 2018, 89(2): 1700248.
[49] Wang X, Fu G, Li W, et al. Numerical simulation and optimization of flash reduction of iron ore particles with hydrogen-rich gases. Powder Technology. 2020, 366: 587-597.

[50] Yilmaz C, Turek T. Modeling and simulation of the use of direct reduced iron in a blast furnace to reduce carbon dioxide emissions. Journal of Cleaner Production. 2017, 164: 1519-1530.
[51] Christopher Manning, Vincent F. Chevrier. Maximizing Iron Unit Yield from Ore to Liquid Steel (Part 1 – Ore Selection). https://www.midrex.com/tech-article/maximizing-iron-unit-yield-from-ore-to-liquid-steel-part-1-ore-selection/.
[52] Hyl Technologies S.A. de C.V. ENERGIRON - The Smart Choice. https://www.tenova.com/product/iron-reduction-technologies/.
[53] Duarte P E, Becerra J, Lizcano C, et al. ENERGIRON direct reduction technology-economical, flexible, environmentally friendly. Acero LatinoAmericano. 2008, 6: 52-58.
[54] Ramakgala C, Danha G. A review of ironmaking by direct reduction processes: Quality requirements and sustainability. Procedia Manufacturing. 2019, 35: 242-245.
[55] Wernet G, Bauer C, Steubing B, et al. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment. 2016, 21(9): 1218-1230.
[56] Spatari S, Betz M, Florin H, et al. Using GaBi 3 to perform life cycle assessment and life cycle engineering. The International Journal of Life Cycle Assessment. 2001, 6(2): 81-84.
[57] World Steel Association. Life cycle inventory methodology report for steel products. https://worldsteel.org/wp-content/uploads/Life-cycle-inventory-methodology-report.pdf.
[58] BAOSTEEL, China Iron and Steel Industry Association. Hot rolling steel plate and strip. Environmental Product Declaration(EPD). https://www.cisa-epd.com/Epd/epdSearch.
[59] China Electronics Technology Group Corporation. CEIC Database. https://www.ceicdata.com.cn/ (in Chinese).
[60] Prism Big Data Research Institute. Data Circle (formerly Tata Database). https://www.shujuquan.com.cn/sequence_1 (in Chinese).
[61] Goto K, Okabe H, Chowdhury F A, et al. Development of novel absorbents for CO2 capture from blast furnace gas. International Journal of Greenhouse Gas Control. 2011, 5(5): 1214-1219.

Demand-side Energy Efficiency in Brazil: Evaluating Heatwave Impacts on Daily Electricity Demand in the Interconnected Power System

Beatriz Nunes Garcia[1*], Talita Cruz[1], Paula Bezerra[1], André F. P. Lucena[1], Roberto Schaeffer[1]

[1] *Energy Planning Program, Graduate School of Engineering, Universidade Federal do Rio de Janeiro, Centro de Tecnologia, Bloco C, Sala 211, Cidade Universitária/Ilha do Fundão, 21941-972 Rio de Janeiro, RJ, Brazil*
Corresponding author: beatriz.garcia@ppe.ufrj.br

A B S T R A C T

The increasing intensity and frequency of heatwaves (HWs) induced by climate change are reshaping energy demand, particularly in the residential and commercial sectors. This study constructs a comprehensive dataset of observed HW events across 201 locations in Brazil over a ten-year period and applies an econometric model to quantify their impact on daily electricity consumption from January 1, 2010, to December 31, 2019, for each subsystem of the Brazilian Interconnected Power System. Results reveal significant regional disparities in HW occurrences, ranging from 18 to 98 events over the decade, with the highest frequencies recorded in the Northeast and Southeast/Central-West subsystems. The econometric model demonstrates that HWs significantly influence daily electricity demand across all subsystems. A 1°C increase in temperature during HW events leads to electricity demand surges of 0.14% in the South, 0.09% in the North, 0.09% in the Southeast/Central-West, and 0.08% in the Northeast. These effects are driven by differences in cooling device ownership, acclimatization needs, and regional climatic conditions. The South, with its historically lower exposure to extreme heat, exhibits the highest sensitivity, whereas the North, characterized by persistently high wet-bulb temperatures, shows a steadier but substantial response. As heatwaves become more frequent and severe, the strain on electricity grids will intensify, increasing the risk of peak load stress and supply shortages. Strengthening energy efficiency policies, expanding high-performance cooling technologies, and improving building insulation are essential to mitigating these vulnerabilities. Without proactive measures, escalating cooling demand will challenge grid stability and sustainability, making energy efficiency a key pillar for a resilient energy future.

Keywords: Extreme events; Adaptation; Empirical model; Climate change, Energy efficiency

Highlights

- Comprehensive panel dataset of heatwave events created for Brazil's SIN subsystems.
- Heatwaves significantly impact electricity demand, with distinct regional sensitivities.
- The South subsystem is the most vulnerable, with lower adaptation to extreme heat.
- Increased cooling demand during heatwaves threatens grid stability and energy security.
- Energy efficiency is key to curbing rising electricity consumption and reducing strain on the power system.

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

EDIT Project Report

Analyzing Low Energy Demand Scenarios: LEDS potential for reducing dependence on CCS and the impacts of production-based and consumption-based carbon pricing in LEDS

February 2025

Tae Yong Jung

Korea International Economic Association

⑦KIEA

TABLE OF CONTENT

1. INTRODUCTION 3

2. Analysis of LEDS Potential for reducing dependence on CCS in achieving Net Zero 5

2.1. Introduction 5

2.2. Literature Review 7

2.3. The Role of CCS in Achieving Mitigation Targets in Korea 13

2.4. Methodology 13

2.5. Data and Assumptions 14

2.6. Model Description 19

2.7. Scenario Analysis 27

2.8. Conclusion 37

3. Impacts of Production-based and Consumption-based carbon pricing in LEDS 39

3.1. Introduction 39

3.2. Literature Review 40

3.3. Data and Methods 41

3.4. Result and Discussion 47

3.5. Conclusion 51

4. Conclusion 53

5. References 55

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 (Professor, Yonsei University)
  - Jongwoo Moon (Research Fellow, Korea Environment Institute)

2. Analysis of LEDS Potential for reducing dependence on CCS in achieving Net Zero

2.1. Introduction

To achieve carbon neutrality, it is also very important to transform the energy system to renewable energy, and the conversion of major sectors such as industry, buildings, and transportation is essential. However, despite this transition, it is expected that there will still be residual emissions, and there is a strong need to utilize CCS for ultimate carbon neutrality. It is very important to achieve carbon neutrality by reducing emissions as much as possible and effectively absorbing, capturing, removing, or utilizing the remaining emissions to reach net-zero emissions. In particular, CCS plays an important role in capturing carbon dioxide emitted by industries that are struggling to reduce greenhouse gases or power plants that use fossil fuels such as coal. However, there are still many uncertainties about the commercialization of CCS technology, the timing of its economic viability, technology development, and securing sites for storage and utilization projects. At this point in time, some carbon capture and utilization technologies are mature and commercialized, but many carbon capture, transportation, utilization, and storage technologies are still in the process of technology development and demonstration for commercialization (Bukar and Asif, 2024; IEA, 2020).

Figure 1. Technology Readiness of CCS technologies

Source: IEA, 2020

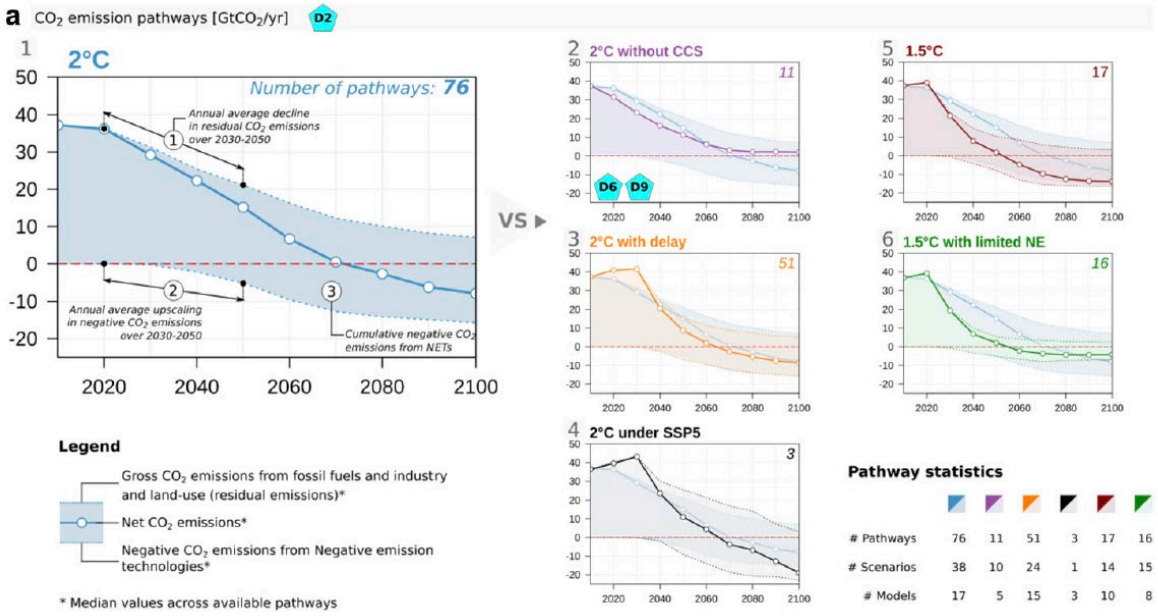
CCS plays an important role in the various scenarios considered in the IPCC AR6 Illustrative Mitigation Pathways and the NGFS Phase 5, and each scenario shows a different use of CCS depending on the level of abatement required by the scenario. The IPCC AR6 IMPs outline emission pathways to limit global warming to below 2 degrees (preferably 1.5 degrees) above pre-industrial levels. Each illustrative mitigation pathway includes distinctive features with a different mix of technologies, policies, and behavioral aspects. The IPCC IMP-LD scenario includes demand-side innovation and efficiency through energy-efficient appliances, behavioral and lifestyle changes through changes in consumption patterns and mobility, and structural changes through circular economy and dematerialization. In this context, this study aims to enhance the global CGE model by reflecting CCS and using it to examine how low-demand measures can reduce the burden on CCS and its economic impact.

2.2. Literature Review

First of all, CCS is analyzed as one of the main options in various carbon neutrality and NDC analysis studies. Leeson et al. (2017) argue that it is important to reduce industrial emissions in order to significantly reduce greenhouse gas emissions, and that CCS technology needs to be included in industrial decarbonization options in order to achieve this goal. In their study, a systematic literature review was conducted on the steel, petrochemical, cement, and power generation sectors, which are areas of interest for reducing greenhouse gas emissions. The steel industry accounts for 31% of industrial greenhouse gas emissions, and the cost of CCS for blast furnaces is estimated to be between $65 and $119 per ton of carbon. The price and abatement potential vary considerably depending on the technology and method. The petrochemical sector accounts for about 10% of global industrial emissions, with 65% coming from boilers and furnaces and 16% from catalytic crackers or gasifiers. The cost of abatement has been shown to range from $40.7 to $121.8 per ton of carbon. However, in the petrochemical industry, emissions originate from combined stacks serving multiple facilities, making it difficult to consolidate them into a single source. Given that emissions are not currently consolidated into a single source, capture rates may be overestimated, leading to an underestimation of costs. Abatement costs also vary considerably between studies, and in many cases, the amount of emissions captured is unknown. Cement accounts for 27% of global industrial emissions, and 60% of these emissions are generated during the calcination process. There is more cost data available for cement than for other industries, and oxy-combustion with calcium looping is more cost-effective than post-combustion amine scrubbing, with an average cost of $39.4 per ton of carbon.

Hilaire et al. (2019) examine the role of negative emission technologies in achieving global climate goals. They examine the role of negative emission technologies in the 1.5°C and 2°C scenarios presented in existing integrated assessment models. In general, rapid and active deployment of negative emission technologies is essential to achieve the 1.5°C scenario, and it is estimated that around 500 GtCO2 of carbon will need to be removed by the end of this century. As many 2°C scenarios require the removal of more than 300 GtCO2 of carbon, NETs are important for achieving global carbon targets. However, it shows that the reliance on negative emission technologies can be significantly reduced by strengthening short-term reduction targets.

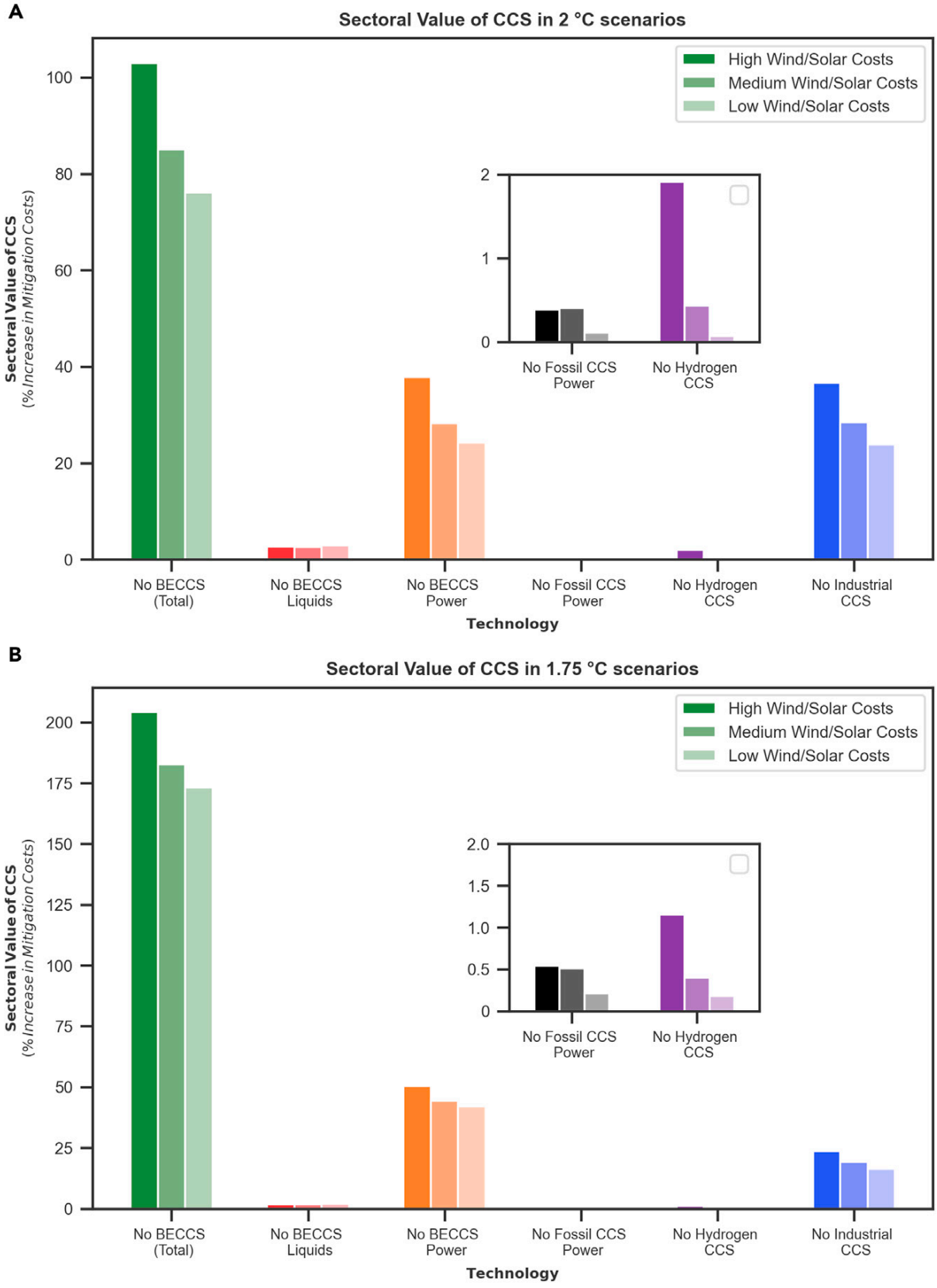
Figure 2. CO2 emission pathways under different scenarios



Source: Hilaire et al.(2019)

Grant et al. (2021) suggest that the rapid decline in the cost of renewable energy could reduce the reliance on CCS in the mitigation pathway. In the IAM's 1.5-degree limit scenario, the median CCS deployment in 2050 is projected to be 85 GtCO2/yr, with a total of 790 GtCO2 captured and stored by the end of the century. However, carbon capture in 2020 is still at a level of 38.5 MtCO2/yr, meaning that there is still considerable scope for expansion. In this study, the value of CCS systems is calculated by varying the availability of CCS by sector, calculating the abatement scenario reflecting the whole technology and the change in total energy system costs. This indicates that the value of CCS can be reduced by between 15% and 96% in various energy sectors as the cost of renewable energy decreases. More specifically, in the power and hydrogen production sectors, renewable energy can directly replace CCS, thus drastically reducing its value. In the industrial sector, however, there are indirect effects from decarbonization and electrification. While the rapid decline in the cost of renewable energy technologies may have an impact on reducing the economic feasibility of CCS, it still shows that CCS can play an important role in the decarbonization of the industrial sector or BECCS.

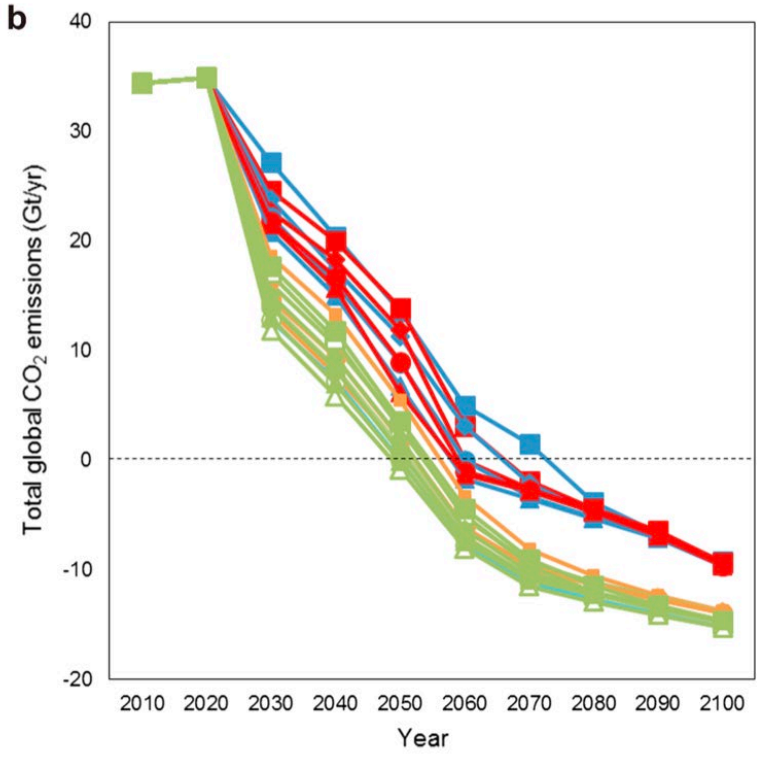
Figure 3. Value of CCS in 2-degree and 1.75-degree scenarios



Source: Grant et al.(2021)

Low demand measures are expected to provide an important opportunity to reduce reliance on CCS. Napp et al. (2019) assess the role of technology in decarbonizing the energy system, with a key research objective being to examine the role of technology in reducing dependence on bioenergy with carbon capture and storage (BECCS). The study, analyzed using the TIAM-Grantham model, which performs linear cost optimization of the global energy system, suggests that reliance on negative emission technologies could be reduced by up to 18% by incorporating new technologies and behavioral changes that lower energy demand. The low-demand scenario assumes, based on previous research, that energy demand for heating, lighting, and appliances can be reduced by 10-20% in the short term and by 50% in the long term. Additionally, it considers that material use in the manufacturing sector could be reduced by approximately 30% in the steel and cement industries and by 20% in the paper industry. If the advanced technology is applied, reliance on BECCS could decreased by about 14% compared to existing technologies, and by 18% when combined with demand reduction measures.

Figure 4. Global CO2 emissions under different scenarios, including low demand scenarios

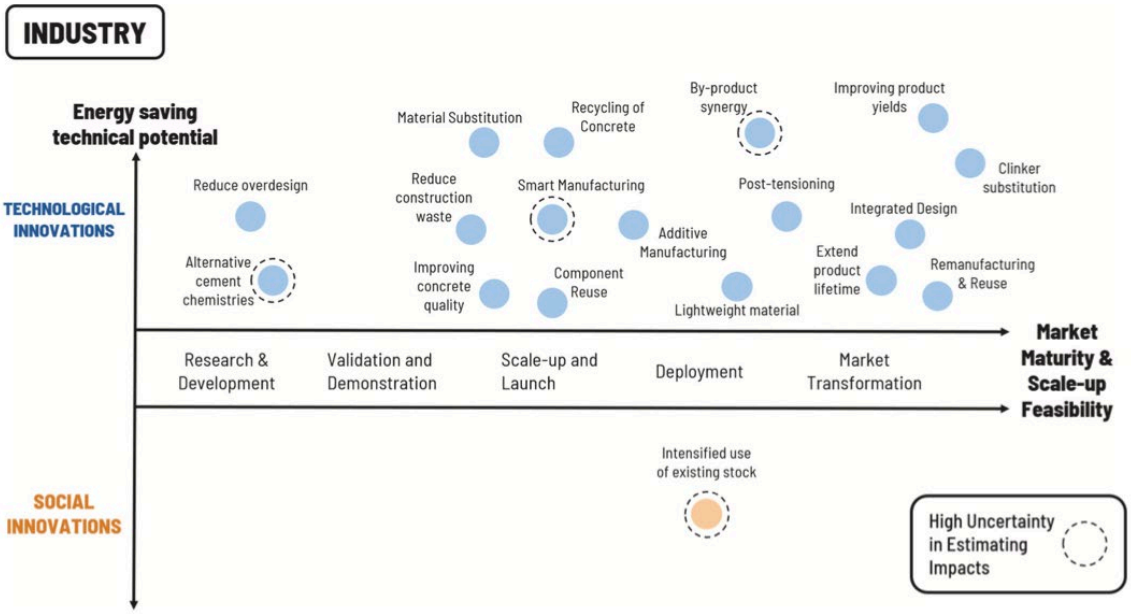


Starting CO_2 price ($/t$CO_2$)	Standard technologies, No price elasticity	Standard technologies, Low costs, No price elasticity	Advanced technologies, no price elasticity	Advanced technologies, Low demands, No price elasticity	Advanced technologies, Low demands, with price elasticity
100	1.85	1.81	1.57	1.53	1.50
150	1.77	1.76	1.51	1.47	1.45
200	1.72	1.73	1.48	1.45	1.42
250	1.69	1.70	1.46	1.43	1.40

Source: Napp et al. (2019)

Khanna et al. (2023) emphasize the importance of the LED pathway in reducing the reliance on CO2 removal required for carbon neutrality. In this regard, this study assesses LED innovations. While the use of technologies such as CCS and CDR plays a crucial role for achieving climate goals such as the 1.5°C target, challenges remain regarding their commercialization, implementation, and long-term sustainability, making reliance on these technologies a complex issue. Khanna et al. (2019) take a closer look at the LED scenario, which focuses on reducing energy demand through demand-side technological and social innovations, and discuss the potential to reduce reliance on CCS. The study looks at examples of changes in buildings, industry, transportation, and lifestyles for demand-side technologies and social innovation, and in the industrial sector, these include design improvements to reduce material demand and a circular economy.

Figure 5. The Potential of Technology and Social Innovation Options

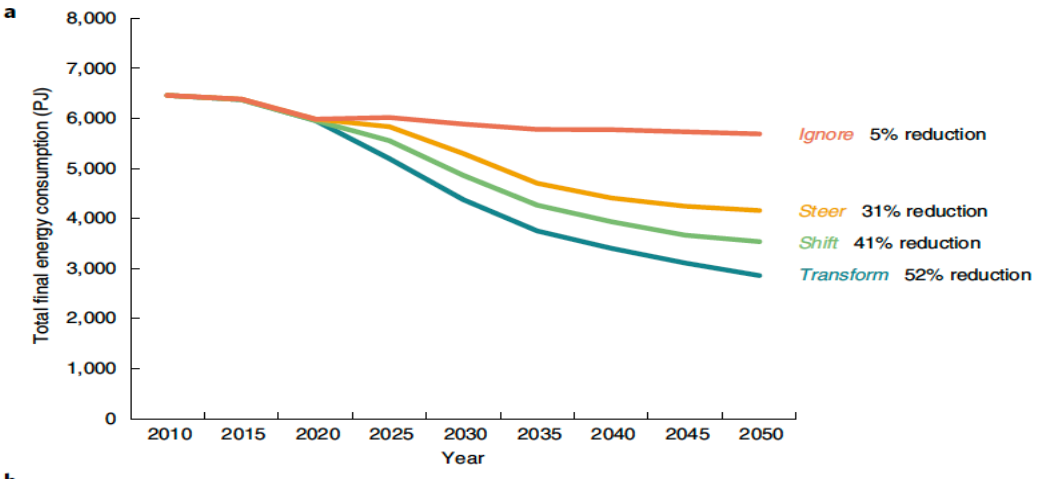


Source: Khanna et al. (2023)

Barrett et al. (2022) examine the reduction in energy demand to meet the UK's carbon neutrality target, and propose ways to reduce reliance on carbon removal technologies such as CCS. To analyze this, four scenarios are presented: the Ignore scenario considers only existing government policies; the Steer scenario is a scenario in which final energy demand is reduced by 31% through energy efficiency improvements, but the carbon neutrality target is not met; the Shift scenario is a scenario where energy demand reduction is actively used to reduce energy demand by 41%; and the Transform scenario is a scenario in which a 52% reduction is

achieved through transformative change and the common benefit of improved quality of life is also achieved.

Figure 6. The Potential of Energy Demand Reductions by each Scenarios



Source: Barrett et al.(2022)

The Steering scenario shows that BECCS and DACs will reduce emissions by 49 MtCO2eq in 2050, and if the remaining emissions gap is to be covered, 76 MtCO2eq will need to be covered. On the other hand, the Shift scenario is expected to reduce the level of reliance to a significant degree by only 37 MtCO2eq, and the Transform scenario is significant in that it can be achieved with nature-based removal alone, without any reliance on BECCS and DAC.

Figure 7. Reliance on CCS by scenario

Source: Barrett et al.(2022)

2.3. The Role of CCS in Achieving Mitigation Targets in Korea

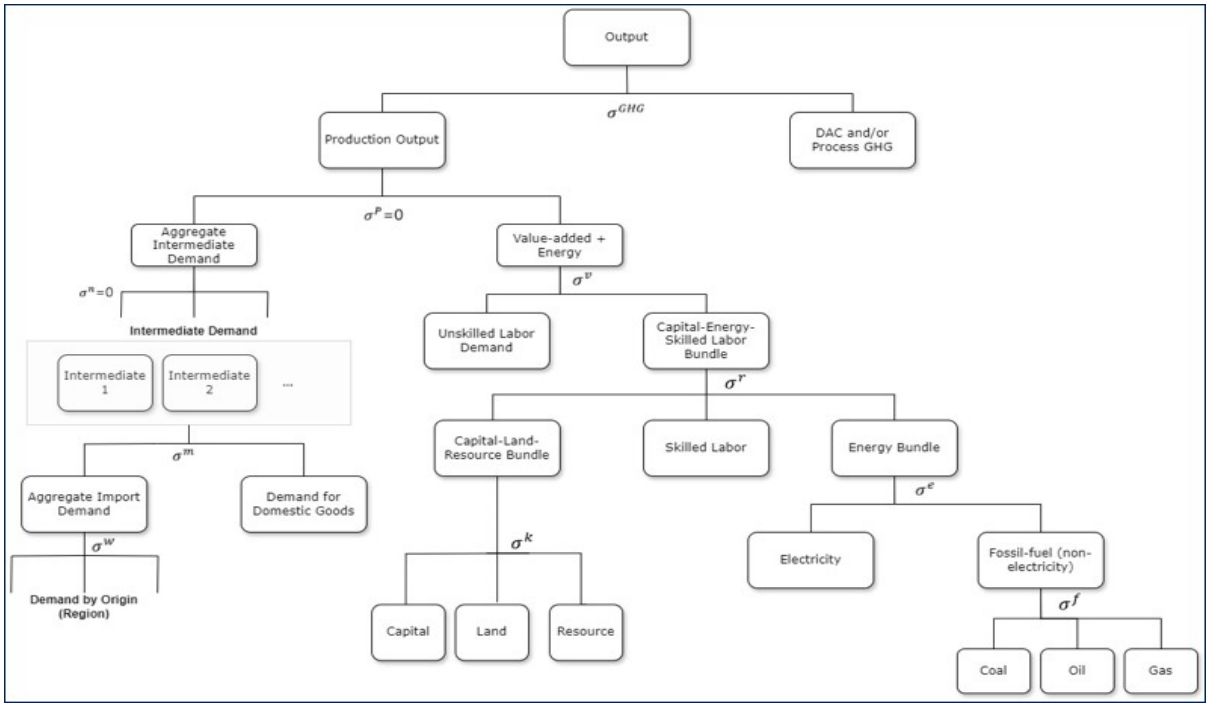
In the case of South Korea, the 2050 carbon neutrality scenario aims to reduce up to 84.6 million tons of carbon dioxide through CCUS. If DAC is also included, the role of CCUS will increase to 92 million tons of CO2. CCS is also expected to play a role in reducing 11.2 million tons of CO2 in the 2030 NDC. Given that national net greenhouse gas emissions were 742.3 million tons in 2018, the use of CCUS is important. In particular, the commercialization of CCUS is important because the steel, petrochemical, and cement industries, which are energy-intensive and emission-intensive, account for a significant portion of Korea's industrial structure. However, there is a shortage of CCS storage sites in Korea, and efforts are being made to secure overseas storage sites.

Given the technical uncertainties, lack of storage capacity, and still insufficient economic feasibility, low-demand measures have the potential to reduce the reliance on CCS in the transition to carbon neutrality while reducing energy consumption. From this perspective, it may be important to examine the impact of CCS on the level of dependence on CCS when CCS is included in the model and low demand measures are considered in the process of transitioning to carbon neutrality and reducing greenhouse gas emissions in Korea.

2.4. Methodology

This research employs the UNICON-G-CGE model, a multi-regional, multi-sectoral computable general equilibrium (CGE) model, to evaluate the economic effects of climate and energy policies, along with various scenarios. The study utilizes the global CGE model and adds CCS technology and industry, which are not included in the GTAP 11 Power database, to assess the economic impacts and the role of CCS and low energy demand measures in achieving mitigation targets. The following figure illustrates the production nesting structure of the UNICON-G-CGE model with CCS.

Figure 8. Production Nesting Structure of UNICON-G-CGE with CCS



Source: Author

2.5. Data and Assumptions

This study applies the GTAP 11 Power Database, which is the most up-to-date database, and aggregates 160 regions/countries into 17 regions.

Table 1: Regional Classification

Label	Description
USA	United States of America
CAN	Canada
WEU	Weatern Europe
KOR	Korea
JPK	Japan
CHI	China
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 and other ASIA
NAF	North Africa
SSA	SubSaharan Africa
SIS	Small Island States

GTAP = Global Trade Analysis Project.
Source(s): Author's own elaboration

The base year of the database is 2017, and there is no information on backstop technologies, such as CCS and Hydrogen. It is therefore necessary to add a new sector to the database representing carbon capture and storage.

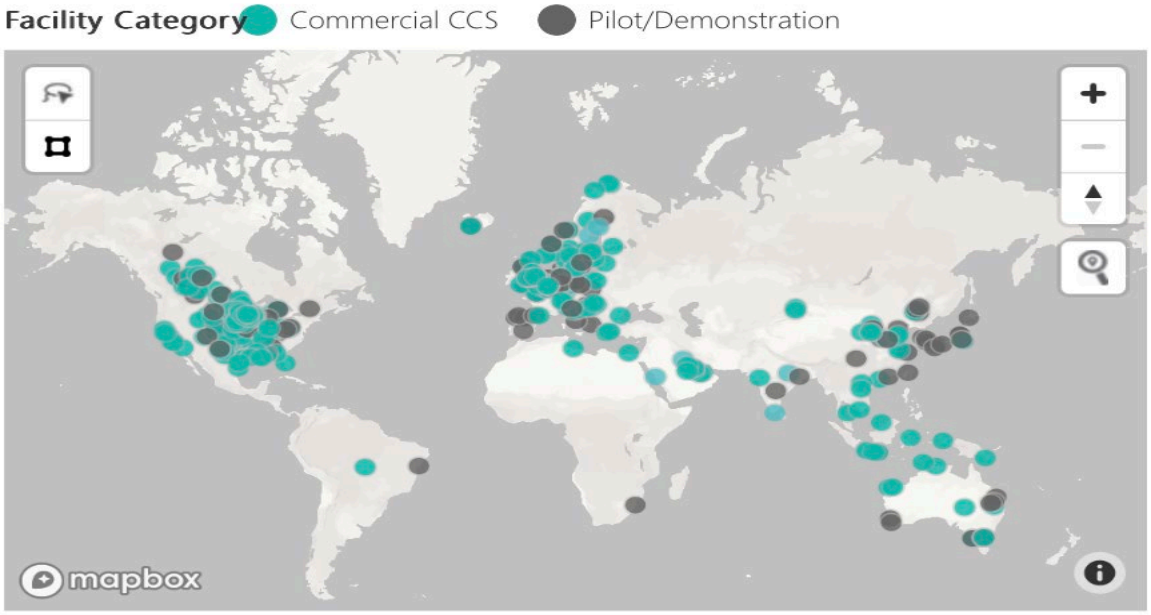
To add the CCS technology, the study utilizes the input cost structure of carbon capture technology from the ERIA (2022). The study uses the share of each input component. ERIA suggests that transportation and storage account for 26.9% of the total cost, so the study assumes that the capital, labor and intermediate components account for the remaining 73.1% of the total cost. However, as it is difficult to identify the detailed information on the intermediate, the study assumes that this intermediate indicates some chemical products used for carbon sequestration.

Table 2. Input Cost Structure

	Cost	Share
Capital	433.05	60.6
Labor	51.95	7.3
Chemical	9.07	1.3
Electricity	28.61	4.0
Transport		26.9
Source: Author's calculation based on ERIA(2022)		

CCS in the industrial and power sectors may have lower abatement costs. However, the current CGE model has limitations in fully accounting for technical and technological components, such as capture and storage potential, as the CCS module is applied at the top level of the production nest. Therefore, the study applies one of the most expensive options, direct air capture, as the reference carbon capture technology at this stage. At the same time, the study applies the learning rate to allow for technology cost reductions.

Figure 9. Global Commercial and Pilot/Demonstration CCS projects



Source: Global CCS Institute CO2RE Homepage, accessed on February 10, 2025.

CCS technologies can be considered in many different industrial sectors, but the study assumes that CCS technologies can be used in coal-fired power generation, gas-fired power generation, iron and steel, petroleum and coal products, mineral products, gas, and chemical industries. To identify the potential demand for CCS by sector, the study utilizes IEA's information on CO2 capture capacity (in 2030) by application.

Table 3. CCS/DAC Demand Sectors

Technology Applications	GTAP Sector	Share
Merchant hydrogen/ammonia	CHM	31.8%
Biofuels	p_c	10.1%
Other fuel transformation	p_c	10.4%
Power and heat	CoalBL, GasBL, GasP, OilBL, OilP	30.8%
Cement	NMM	7.8%
Iron and steel	I_S	1.6%
Other industry	Others*	7.5%

Source: Author's calculation based on IEA(2024)'s CO2 Capture Capacity by Technology in 2030.
Note 1: From IEA(2024), the Direct Air Capture does not have a specific sector, so the study calculates the share of the other technology applications and allocates to each model sectors. Also, the study assumes that CCS/DAC are applied to non-energy, key industry sectors.
Note 2: Other industry includes GTAP sectors included in Chemical, Metal, and Mineral sectors in this analysis, which can be considered as hard-to-abate sectors

Estimates of the current global market size for CCS vary between sources, and there is limited information on the regional market size for CCS, as there are limited commercialized

(or pilot/demonstration) CCS projects worldwide, and current commercial and pilot/demonstration CCS projects are largely located in the US, Europe, and some Asian countries. Furthermore, the global market size in 2023 is approximately 2.4 billion USD (Statista, 2025). Therefore, in this analysis, the study assumes that the global CCS market size is around 2.4 billion USD, divided between the major economies in North America, Europe, and Asia. Initially, the study estimates the CCS industry size in Korea to be 20 million USD. In this model, the carbon capture, transport, and storage are not classified separately, but are combined into a single node that reflects the overall cost of the CCS. In addition, the uncertainty in CCS costs is quite high, and there are significant differences between regions and technology options. There is significant price uncertainty for all capture, transport, and storage components.

There are only a limited number of cases where costs are broken down by region in detail. Estimates of the cost of direct air capture vary between studies, ranging from $500 to $1,000. The WEForum suggests a range of $600 to $1,000, and Forbes(2024) suggests a range of $500 to $1,000. Sievert et al. (2024) suggest a range of $521 to $894 for liquid solvent DACCS with an initial capacity. Lebling et al. (2022) suggest a range of $250 to $600; thus, the estimated costs of direct air capture show a significant difference.

There is a limitation in reflecting all uncertainties in this model, so this study utilizes the cost information from Sendi et al. (2024). The study utilizes Sendi et al.'s (2024) gross levelized cost of DAC(LCOD) for HighWACC, AllTech regional costs. The regional costs and the average cost of the regional LCODs are similar to the cost range of the previous study. To account for the technology development, the study assumes a learning rate of 10% for DAC/CCS technology deployment.

Table 4. Regional LCOD and Ratio-to-Average LCOD

Model Region	Sendi et al.(2024)'s Region	LCOD ($/tCO2)	Ratio to Average LCOD
kor	East Asia	691	0.876
can	USA	582	0.738
usa	USA	582	0.738
WEU	Europe	562	0.712
JPK	East Asia	691	0.876
ANZ	Australia	655	0.830
CEE	Europe	562	0.712
FSU	Europe	562	0.712
MDE	Middle East	720	0.912
CAM	Latin America	1,013	1.284
SAM	Latin America	1,013	1.284

SAS	India	900	1.141
SEA	Southeast Asia	822	1.042
CHI	East Asia	691	0.876
NAF	Afirca	1,157	1.466
SSA	Afirca	1,157	1.466
SIS	Southeast Asia	822	1.042

Source: Author; Sendi et al.(2024).
Note: The cost information is extracted from the regional LCOD of AllTech, High WACC from Supplement Figure 4. Due to different regional classifications of the study and Sendi et al.(2024), the author allocates the regional LCODs from Sendi et al.(2024) to the regional classification of the study.

The study classifies the total of 160 regions into 17 regions. It identifies Korea, Japan, China, the US and Canada as an individual region, and classifies other regions according to their regional characteristics.

For the sectoral aggregation, 76 sectors of the GTAP power database are aggregated into 21 sectors, and the 'CCS/DAC' sector is also included. Thus, a total of 22 sectors are included in the study.

Table 5. Model Sectors and Global Trade Analysis Project Code

Label	Description	GTAP sectors code
ely	Non-renewable electricity	CoalBL, GasBL, OilBL, GasP, OilP, TnD
REN	Other Renewable electricity	OtherBL, HydroBL, HydroP
WIN	Wind (electricity)	WindBL
SOL	Solar (electricity)	SolarP
DAC	DAC/CCS	-*
coa	Coal	COA
oil	Oil	OIL
gas	Gas	GAS, GDT
p_c	Coal and petroleum products	P_C
AGR	Agriculture	PDR, WHT, GRO, V_F, OSD, C_B, PFB, OCR, CTL, OAP, RMK, WOL, FRS, FSH
Mineral	Mineral	OXT
Food	Food and food products	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	ELE, EEQ
Machine	Machine	MVH, OTN, OME, OMF
Construc	Construction	CNS
Service	Service	OSG, EDU, HHT, WTR, AFS, TRD, WHS, OTP, WTP, ATP, CMN, OFI, INS, RSA, OBS, ROS

Trans	Transport	OTP, WTP, ATP
Dwell	Dwelling	DWE

* DAC/CCS sector is not included in GTAP database, so a new sector is additionally created
Source(s): Author's own elaboration.

This study utilizes the GTAP 11 Power Database (Aguiar et al., 2022), so the base year for the study is 2017. The study aims to analyze the potential of low energy demand measures to reduce reliance on CCS, and this CGE model allows for the analysis of the impacts on economic variables, such as GDP and GDI, as well as on climate-related variables, such as temperature increase and global CO2 emissions. The model distinguishes between skilled and unskilled employment based on the GTAP 11 database. The GTAP 11 database classifies five types of occupations from the International Labour Organisation into two groups, which are skilled and unskilled employment[1].

2.6. Model Description[2]

A Computable General Equilibrium (CGE) 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 be used to conduct policy experiments that impact numerous countries and sectors simultaneously.

The analysis using the CGE model offers a comprehensive overview of the impacts of transitions to 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.

[1] Unskilled Labor includes clearks, service/shop, and agriculture and other workers. Skilled labor includes tech/associate professionals and officials/managers/professionals.
[2] This section is prepared based on the previous EDITS report

The study utilizes a global multi-regional dynamic recursive CGE model with a 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 10] illustrates the nesting structure of the production technology, where each node within the nested framework represents a CES function expressed in calibrated share forms.

$$\boldsymbol{Q = \overline{Q}\left[\sum_i \theta_i \left(\frac{X_i}{\overline{X_i}}\right)^{\rho}\right]^{1/\rho}, \rho = \frac{\sigma-1}{\sigma}},$$

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:

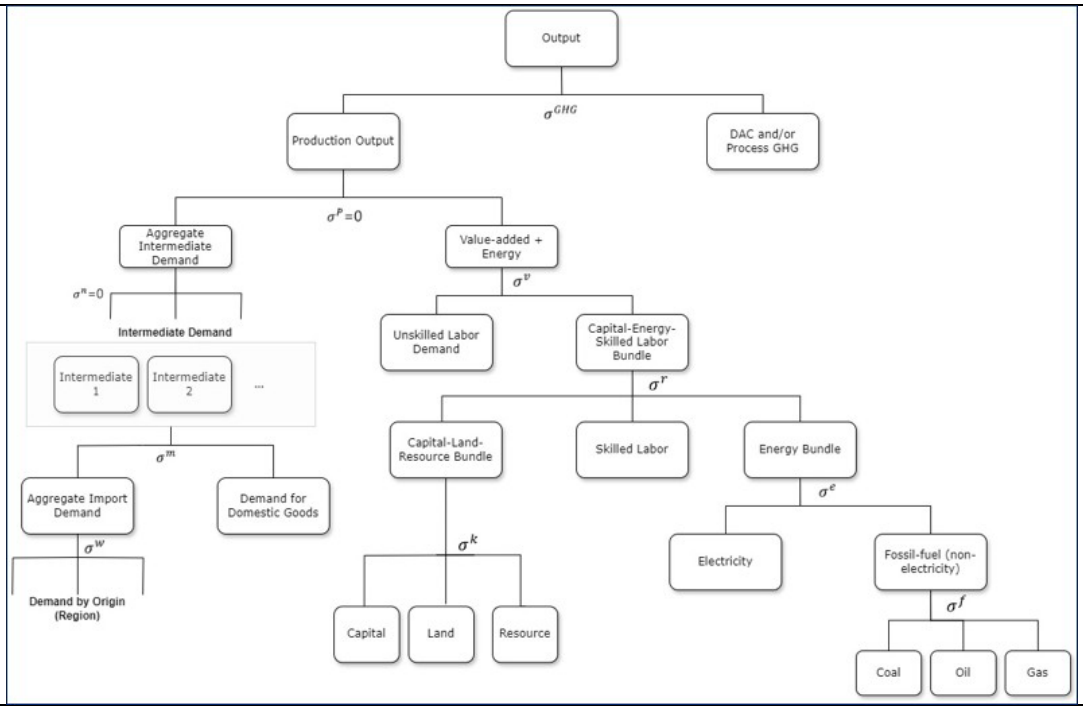
$$\boldsymbol{X_i = \lambda_i^{\sigma-1}\theta_i \left(\frac{\overline{\beta}}{\overline{P_i}}\right)^{1-\sigma}\left(\frac{\beta}{P_i}\right)^{\sigma} Q, \beta = \overline{\beta}\left[\sum_i \theta_i \left(\frac{P_i}{\overline{P_i}}\right)^{1-\sigma}\right]^{1/(1-\sigma)}},$$

where P_i is the price of i-th input and β is the output price.

The equilibrium conditions outlined above are applicable across all CES technologies, encompassing every sub-node within the nested CES functions. These conditions extend to various economic relationships, including substitution between domestic and imported goods, transformation between domestic and export demand, and competition between regions for international transport services.

[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.

Figure 10. Nesting Structure of UNICON-G-CGE Model with CCS



Source: Author's own elaboration.

Dynamic recursive CGE models establish an equilibrium for each time period. In this framework, households are depicted as making decisions in the present time, while the model incorporates dynamic features that allow physical capital to accumulate over time. This accumulated capital is subsequently utilized in the production processes of future periods, representing the continuous development of the economy's productive capabilities.

The international trade component of the model uses the Armington specification assumption within a two-level nested CES structure. At the first level, domestic agents choose between domestically produced goods and a composite of imported goods. At the next level, they allocate their demand for these imported goods across different trading partners (Jung et al., 2021).

In the household sector, a Cobb-Douglas utility function is applied. The government imposes various taxes, including income taxes, taxes on production factors, consumption taxes, and tariffs. Government expenditure is modeled using a Cobb-Douglas production function, with total consumption set as a fixed share of real GDP. To ensure fiscal balance, the government maintains its budget surplus or deficit at the base year level, adjusting income tax rates endogenously as necessary. The model assumes that each region's current account surplus or deficit remains fixed at its base year value, thus maintaining external balance within the system.

Table 6: 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)	$(1-ti) \cdot \sum_f PF_f QF_f = \sum_i P_i \cdot (1+tc_i) \cdot QC_i + HSaving$ $\sum_f tf_f PF_f QF_f + ti \sum_f PF_f QF_f + \sum_i \left(tc_i P_i QC_i + tp_i PP_i QP_i + \sum_j t_{ij} P_i QAP_{ij} \right) + \sum_{(r',i)} tariff_{r',r,i} Qtrade_{r',r,i} = \sum_i P_i QG_i + GovSaving$ $\sum_i P_i QINV_i = HSaving + GovSaving + ForeignSaving$

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.

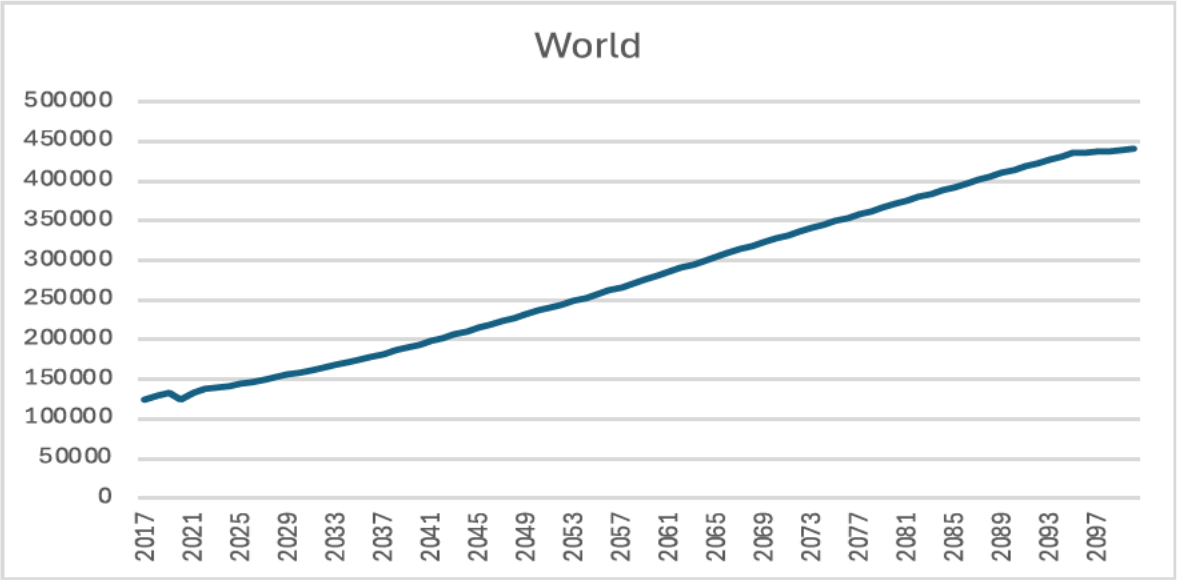
Table 7: Key Parameters

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}	1 0 for fossil-fuel
Substitution between renewable and nonrenewable electricity	σ^{l}	4
Substitution between fossil energies (Coal and Oil and Gas)	σ^{f}	0.55 0 for fossil-fuel
Substitution between Oil and Gas	σ^{OG}	1 for new 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 based on ENV-Linkages Model

The authors utilized the GTAP 11 Power database to construct a Global Social Accounting Matrix, and the model utilizes the SSP 2 scenario from SSP version 3.1 (released July 2024). The GDP projections of the SSP 2 scenario start from 2025. To include the impact of COVID-19, the study utilizes real GDP, PPP data from the World Bank until 2022. Also, the SSP 2 scenario provides GDP projections for every 5 years, so the study assumes that each country's GDP increases at the same growth rate during each period. The model is calibrated by adjusting labor factor productivity to reproduce the SSP2 GDP projection.

Figure 11. Global GDP (SSP 2) (unit: billion USD)



Note: GDP, PPP (Billion USD)

The study applies different learning rates to each renewable and CCS/DAC technology. For renewable electricity technologies, the study classifies the global and local components and applies different learning rates to the local and global parts based on the literature review (Zhang et al., 2020; Huenteler et al., 2016; NREL, 2023). The cost structure of wind technology indicates that a large portion consists of wind turbines (blades, tower, etc.). The cost of solar technology indicates that solar technology contains more local components. Thus, the study identifies 70% of wind technology as a global component and 34% of solar technology as a global component. The remaining parts are local components. For the other renewables, the study simply defines the global and local cost components as 50:50.

For the global and local learning rates, the study assumes a global learning rate of 17% for solar and 12% for wind, based on (Rubin et al., 2015; Zhang et al., 2020; Huenteler et al., 2016). For other renewables, the study assumes a global learning rate of 11%. For the local learning rates, the study assumes that the relatively lower learning rates for renewable technologies, compared to global learning rates are due to the fact that local cost components contain more soft costs, such as labor costs. It assumes a slightly higher local learning rate in the developed region than that in the developing region. The study assumes 6% for the Global North and 4% for the Global South on wind, 8% for the Global North and 5% for the Global South on solar, and 5% for the Global North and 4% for the Global South on other renewables. Lastly, the study assumes a learning rate of 10% for DAC/CCS.

Table 8. Target % GHG Emission Reductions in 2030, 2040, and 2050 (compared to 2017 emissions) (unit: %)

	2030	2040	2050
NAF	15.8%	13.6%	10.6%
SSA	15.8%	13.6%	10.6%
ANZ	-30.9%	-54.9%	-59.6%
CAN	-34.1%	-66.5%	-74.6%
CEE	-44.0%	-65.1%	-77.9%
CAM	-5.4%	-21.5%	-33.7%
SAM	-5.4%	-21.5%	-33.7%
CHI	-18.6%	-59.2%	-75.3%
FSU	-12.6%	-43.5%	-64.4%
JPK	-35.6%	-64.0%	-74.6%
KOR	-28.6%	-58.1%	-77.0%
MDE	-11.0%	-41.2%	-60.9%
SAS	21.6%	0.1%	-20.2%
SEA	10.2%	-32.9%	-53.8%
SIS	-29.4%	-51.8%	-68.7%
USA	-33.4%	-57.7%	-70.5%
WEU	-39.5%	-66.6%	-79.5%

Although the dynamic CGE model is useful for conducting various scenario analyses and assessing the effects of the net-zero transition on the global economy, it has several limitations. Primarily, the CGE model relies on the assumption of constant a elasticity of substitution and exhibits rigidities in its production and trade structures. This makes it difficult to account for changes in elasticities of substitution caused by different factors. Keeping parameters such as elasticities of substitution fixed over an extended time horizon may fail to capture potential shifts in these values in the future. Additionally, the model struggles to incorporate emerging industries or technologies, such as hydrogen, due to the scarcity of available data. Finally, the model is based on a relatively outdated Global Social Accounting Matrix derived from the GTAP 11 power database. While GTAP 11 remains the most comprehensive and up-to-date database for global CGE analysis, its input-output tables are based on 2017 data, which may not accurately reflect the current state of the global economy.

The study includes a climate module from the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model. Although the study utilizes the CGE model with CO2 emissions only, other non-CO2 emissions are calculated externally based on the output

of each sector. To do so, non-CO2 greenhouse gas emission coefficients are calculated by dividing non-CO2 greenhouse gas emissions (by gas) by the sectoral output in the base year. These coefficients are then multiplied by the sectoral output in each year to calculate the non-CO2 greenhouse gas emissions.

The study identifies low energy demand measures as improvements in energy efficiency in the industrial sector and in household energy and electricity consumption. The study assumes an energy efficiency improvement of 1% per year for the Global North and 1.5% per year for the Global South. The study also adjusts the share parameter of household energy and electricity consumption to decrease by 2% per year for the Global North and 1.5% for the Global South. Lastly, the study assumes that higher elasticities of substitution of energy and electricity technologies are a potential representation of the low-demand scenario in the CGE model. It illustrates that industries become more elastic to price changes to change their energy and electricity consumption behavior and to shift their energy consumption towards low-carbon sources. In other words, a slight shift in the relative price of commodities results in a larger change in their relative consumption levels. It suggests that policies and measures promoting low energy demand behavior could induce households and industries to adjust their consumption and production patterns towards less energy and carbon intensive options. Therefore, the study establishes four scenarios, each of which is described in the table below.

Table 9. Description of Scenarios

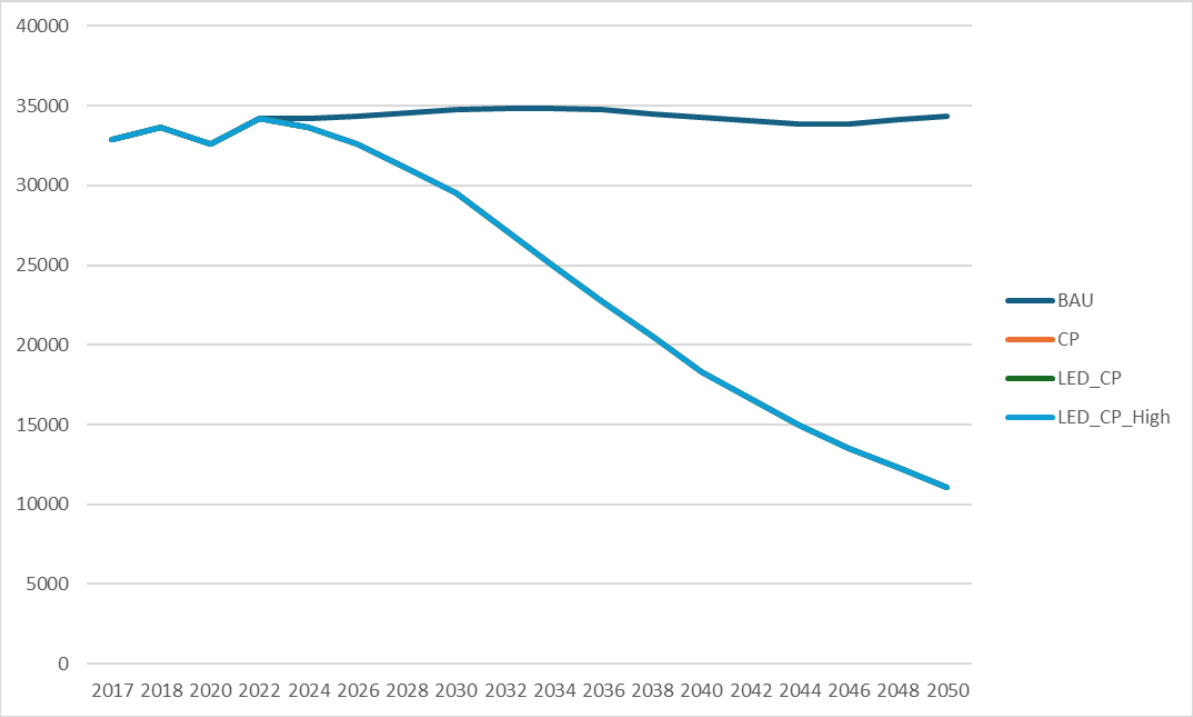
Scenario	Key assumptions
BAU (Current Policy)	Baseline scenario GDP and population forecast in SSP2 scenarios The regional emissions follow the current policy scenario's emission pathway.
CP	Achieving the mitigation targets (below 2-degree scenario) by 2030, 2040, and 2050 via carbon pricing (endogenously determined by the model)
LED_CP	CP Scenario + Low Energy Demand measures (energy efficiency improvement and household energy consumption adjustment)
LED_CP_High	LED_CP Scenario with higher elasticities of subsitution (+10%)

2.7. Scenario Analysis

2.7.1. Global

The results of this study show that CO2 emissions vary considerably depending on the scenario. The BAU (Current Policy) scenario projects a slight increase in global CO2 emissions until 2030, followed by stabilization. If carbon pricing aligned with the below 2-degree emissions target is implemented, global CO2 emissions are expected to decline by approximately 66% by 2050 compared to the base year of 2017. In this study, the emissions in the other two scenarios (LED_CP and LED_CP_High) are set to the same level as in the CP scenario to examine the effects of LED measures.

Figure 12. Global CO2 Emissions (Unit: MtCO2eq)



Since the study assumes the BAU as the current policy that each country follows the current policy emissions pathway, the carbon price will be partially reflected to follow the corresponding emissions pathway. In some regions, such as the WEU, the carbon price gap between BAU and other scenarios is relatively small because significant reductions are already being made with the current policy scenario. The carbon prices of the CP, LED_CP, and LED_CP_High scenarios, which follow the mitigation pathways by region, appear to be at

similar levels. There are some mixed results by region, with some regions showing slightly higher carbon prices under the LED scenarios (compared to the CP scenario), while the other regions show slightly lower carbon prices under the LED scenario (compared to the CP scenarios).

As shown in the mitigation targets above, developed countries tend to have higher mitigation targets but start to mitigate at a earlier period. On the other hand, developing countries reduce their emissions more steeply in the later periods, which may eventually lead to relatively higher carbon prices. In addition, regional carbon prices may be affected by the cost of the CCS/DAC technology, which is a backstop technology. Therefore, carbon prices may be lower in countries where the price of the backstop technology is relatively lower in 2050.

Figure 13. Carbon Price in 2030 by Region (unit: 1,000 USD)

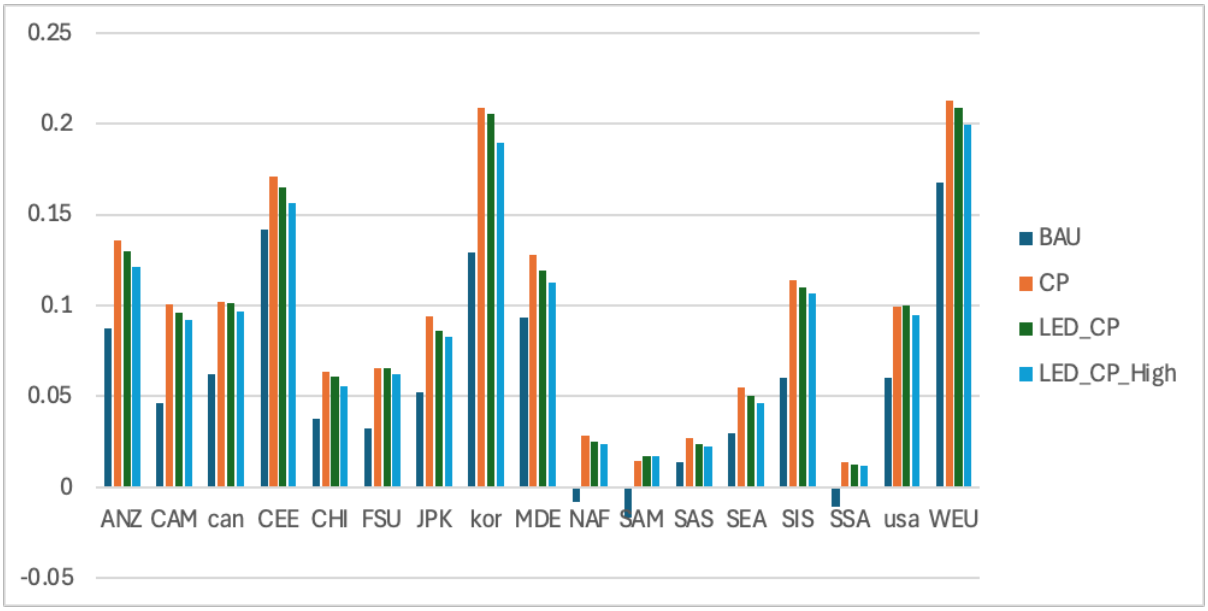
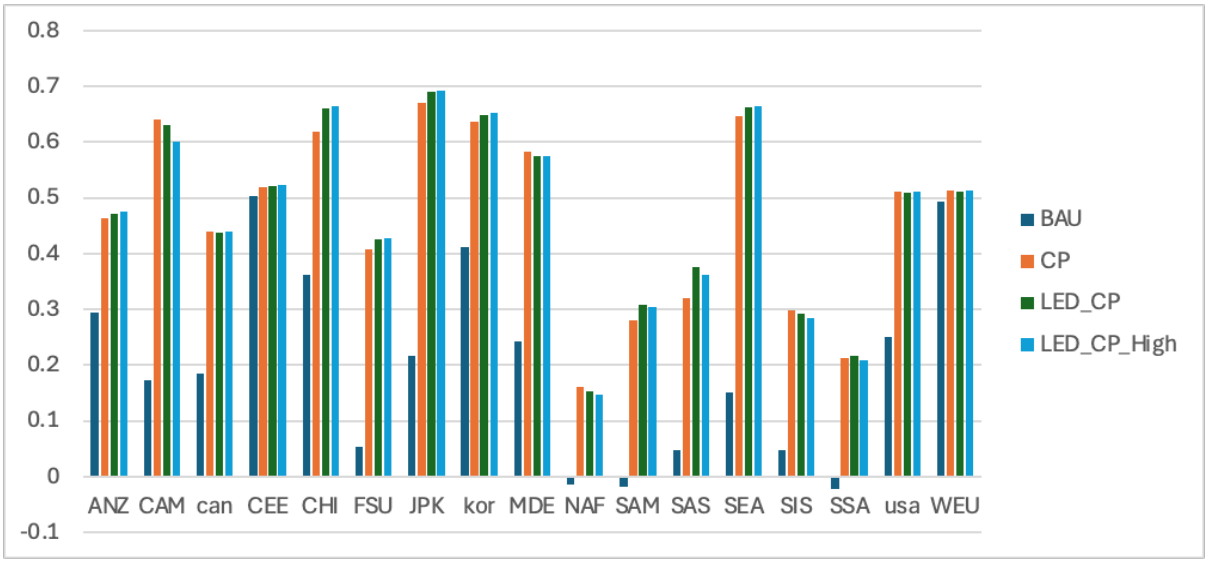
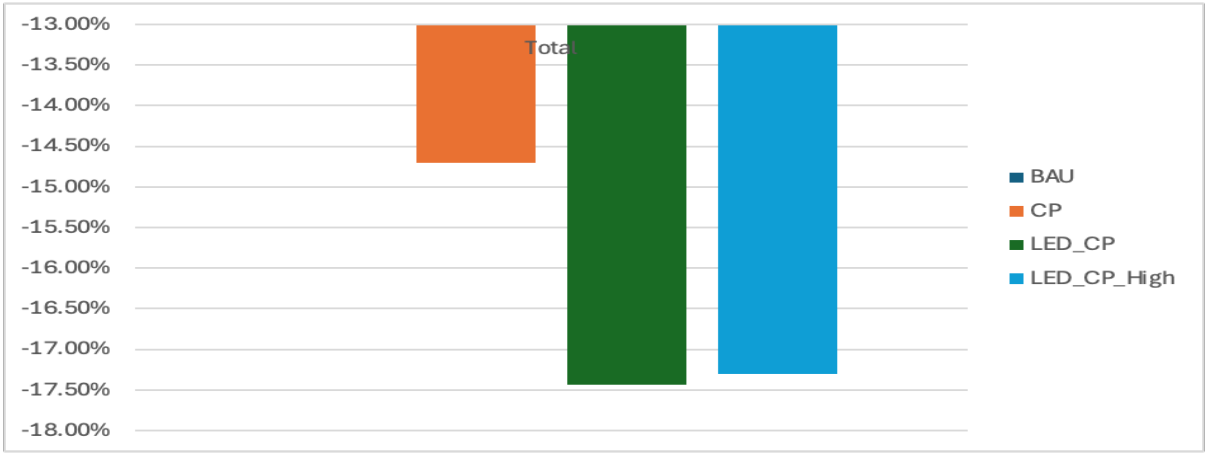


Figure 14. Carbon Price in 2050 by Region (unit: 1,000 USD)



The global energy consumption reduction can be achieved more than 14.5% compared to BAU if carbon pricing is applied to achieve the 2-degree emissions pathway. When some of the LED measures defined in this study, such as energy efficiency improvement and household energy consumption reductions, are included, additional reductions in final energy consumption can be achieved.

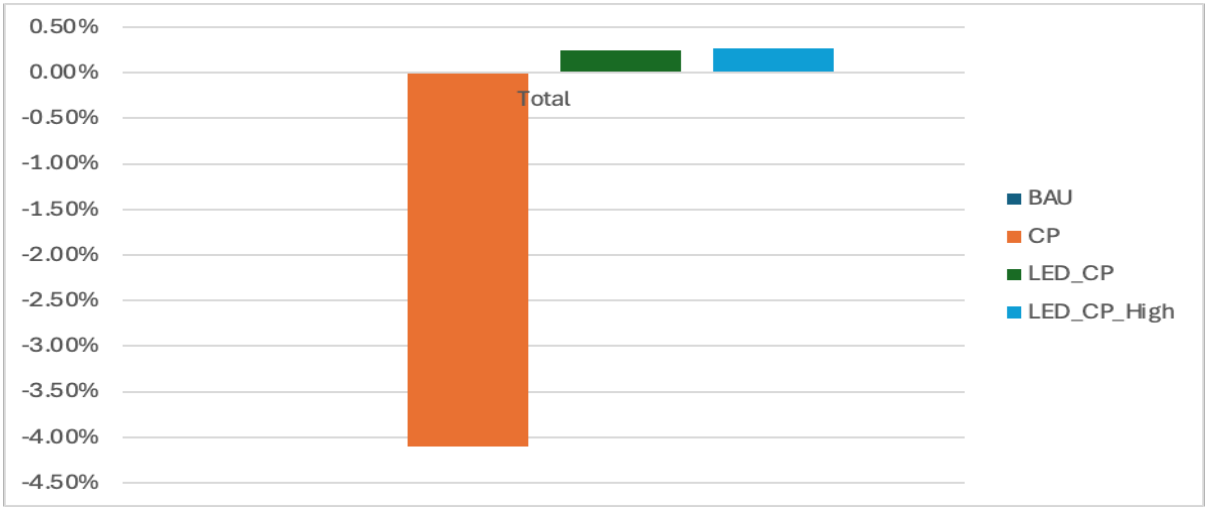
Figure 15. Changes in global Final Energy Demand (2022-2050) (Unit: % difference from BAU)



The figure below shows the change in real GDP (2022-2050) compared to the BAU (Current Policy) scenario. It shows a slight loss in global real GDP if a stronger reduction target is achieved, but the loss is limited to around 4% compared to the BAU scenario. A possible

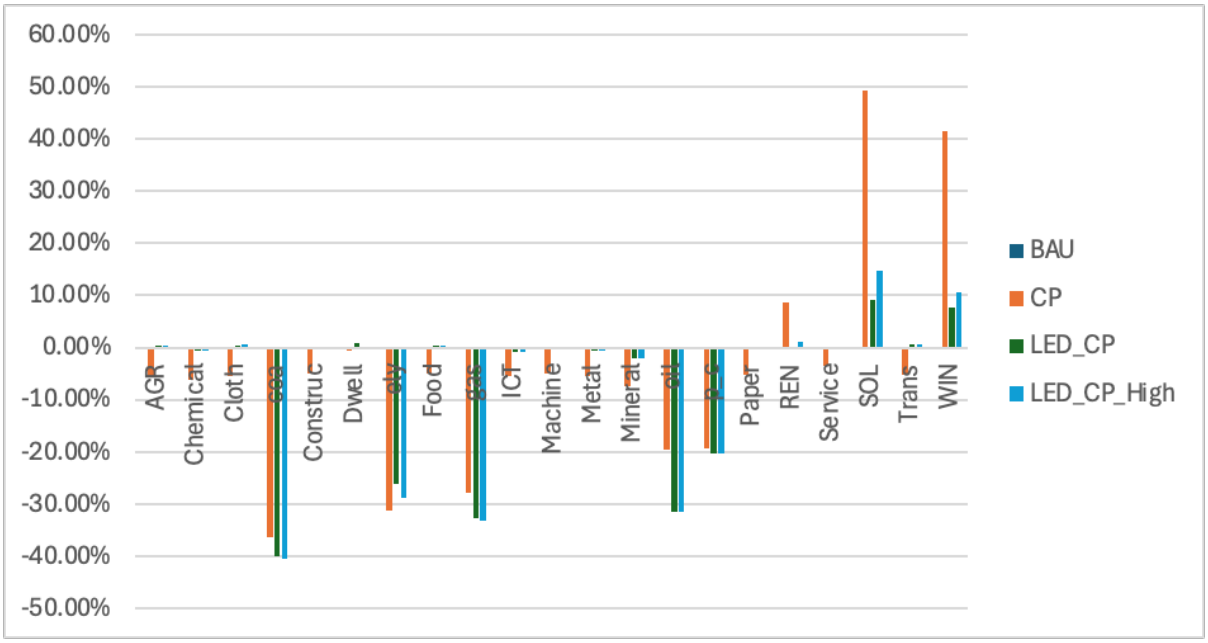
reason for this may be that the Current Policy scenario already achieves substantial emission reductions in some regions, so that the costs of additional reductions are relatively low. Also, as the reduction target is strengthened, a larger utilization of carbon capture may limit some of the real GDP losses. The inclusion of some LED measures suggests that some positive economic outcomes can be expected. Increased productivity due to improved energy efficiency can lead to higher output and some positive economic effects. In addition, energy efficiency improvements may lead to cheaper energy sources for production, which may lead to some positive economic effects.

Figure 16. Changes in real GDP (2022-2050) (% difference from BAU)



The global sectoral production indicates that the production of fossil fuels, such as coal, gas, and oil, as well as non-renewable electricity, decreases substantially, while the production of renewable electricity increases significantly.

Figure 17. Changes in Global Production by Sector (2022-2050) (% difference from BAU) (Excluding DAC/CCS sector)



The impact of LED measures on the dependence on carbon capture is shown in the figure below. The use of global carbon capture increases significantly from the mid-2030s, and the emissions pathway to achieve the 2-degree target results in approximately 5.36 GtCO2 of carbon capture in 2050. If some LED measures are included, the carbon sequestration burden can be slightly reduced to 5.21 GtCO2. If higher energy elasticities of substitution are included, the burden can be further reduced to 4.86 GtCO2. While the study considers only limited LED measures, it shows some potential for reducing the reliance on carbon capture in meeting mitigation targets.

Figure 18. Global Carbon Capture by Scenario (2022-2050) (unit: MtCO2eq)

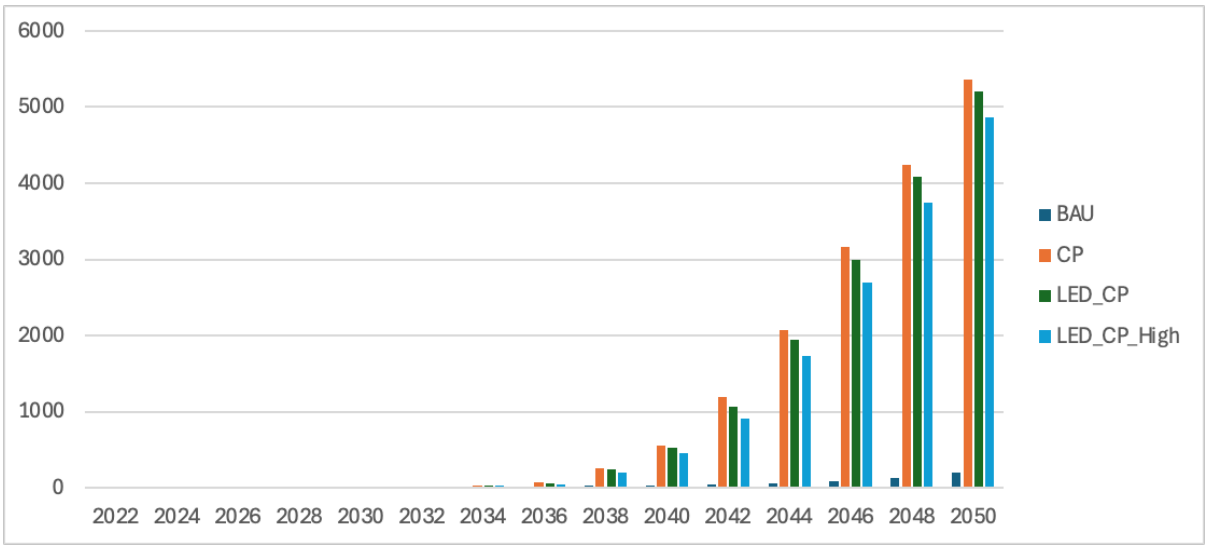
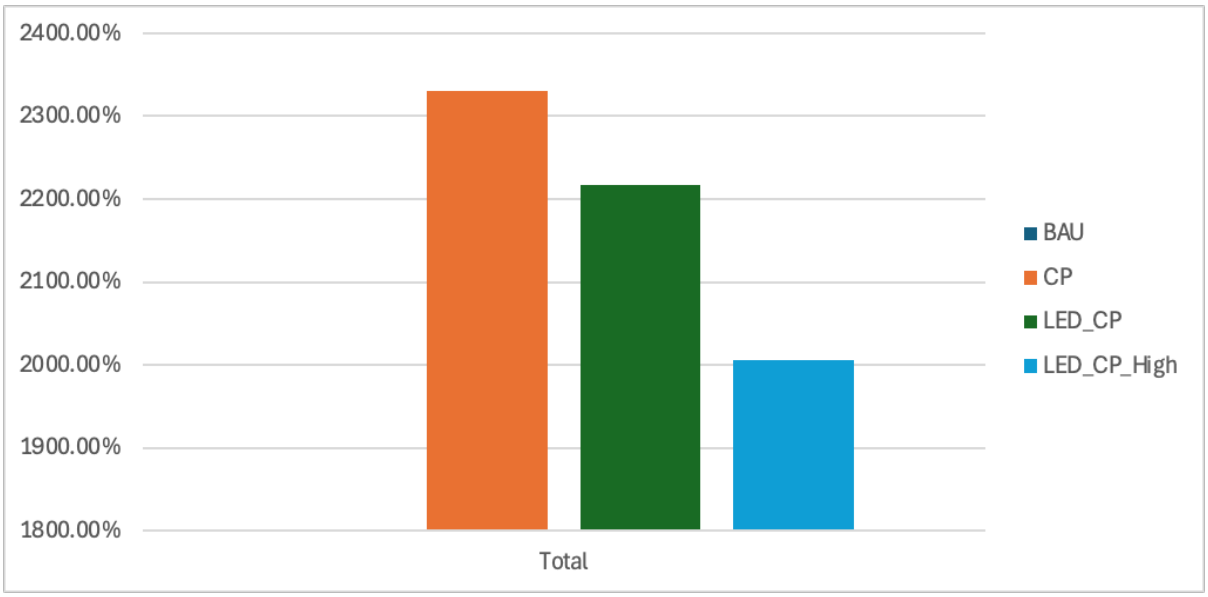


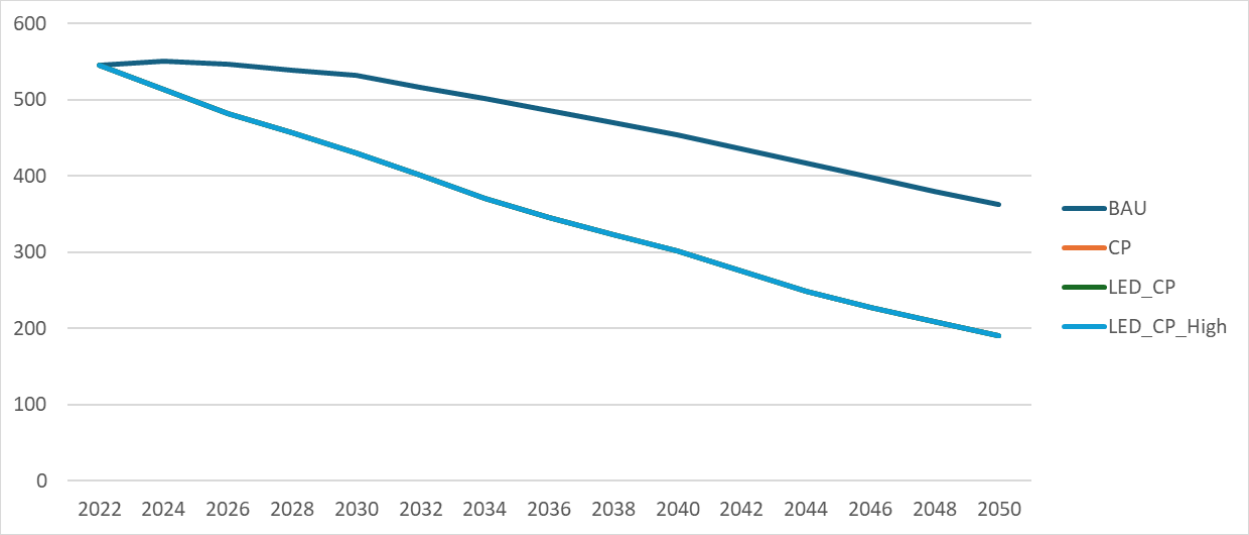
Figure 19. Changes in Global Carbon Capture (2022-2050) (% difference from BAU)



2.7.2. Korea

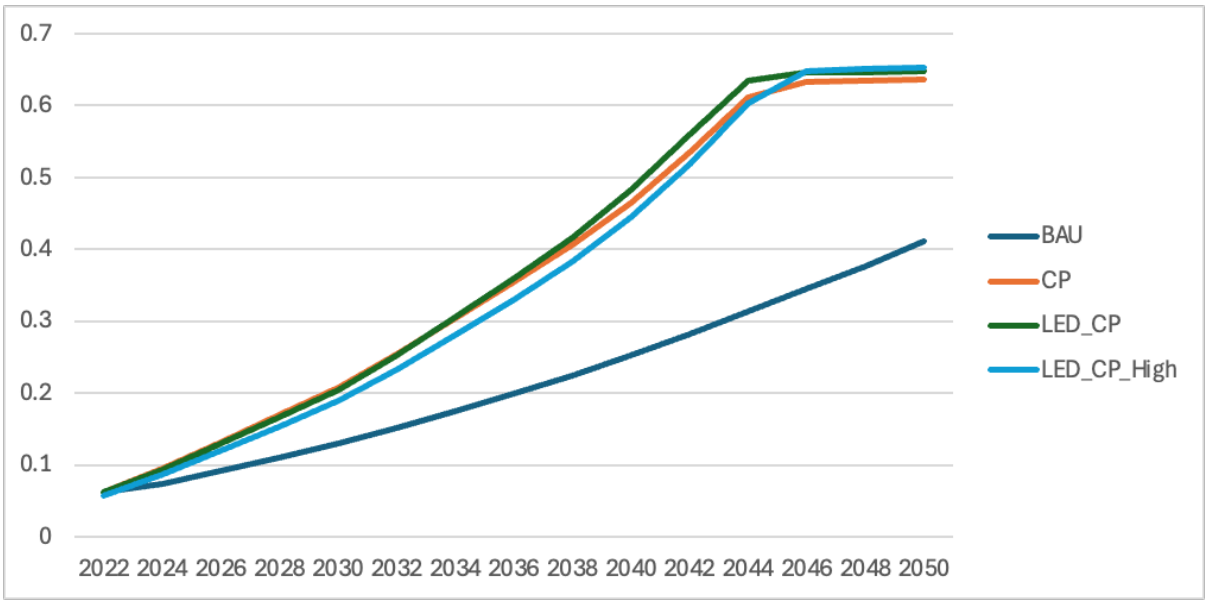
In the case of Korea, CO2 emissions gradually decrease in the BAU scenario, and they decrease even further in the CP scenario, which aims to achieve the below 2-degree emissions target. In 2050, it achieves about 68% of the emission reductions compared to the base year of 2017.

Figure 20. Changes in CO2 emissions in Korea (2022-2050) (% difference from BAU)



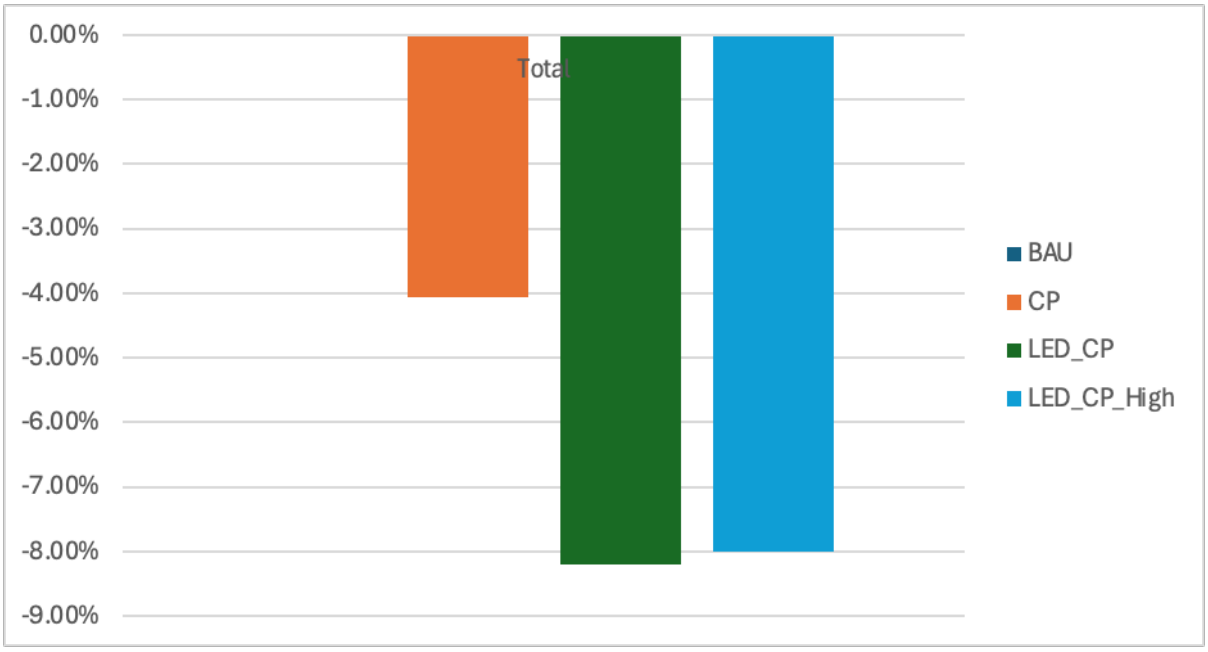
Carbon prices in Korea increase gradually in the BAU scenario, reaching about $400 per ton of CO2 in 2050. In the CP scenario, the carbon price can rise to over $600 per ton of CO2 in the mid-2040s. The flattening of carbon prices thereafter can be attributed to the utilization of the carbon capture option, which is a backstop technology.

Figure 21. Carbon Price Trajectories of Korea (unit: $1,000 USD)



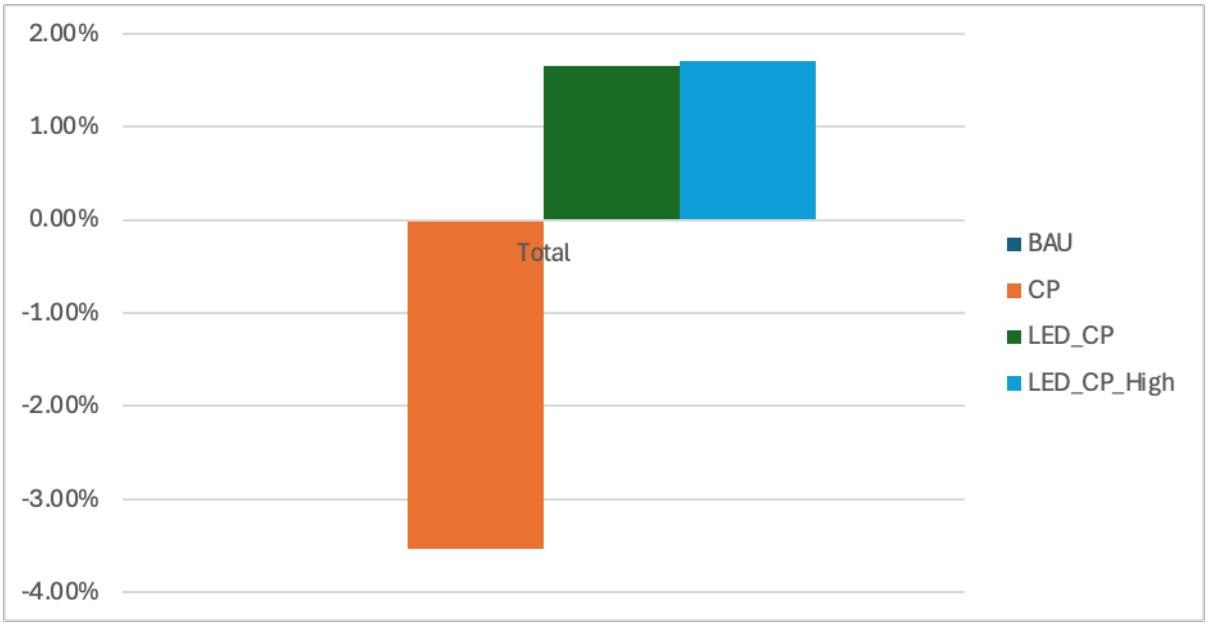
For the changes in final energy consumption, it shows that final energy consumption can be reduced by about 4.06% when carbon prices are taken into account to achieve the mitigation targets. The change in final energy consumption of about 4% is relatively small compared to the changes in global final energy consumption. When some LED measures are taken into account, it also shows that a reduction in final energy consumption of about 8% can be achieved compared to BAU.

Figure 22. Changes in Final Energy Demand in Korea (2022-2050) (% difference from BAU)



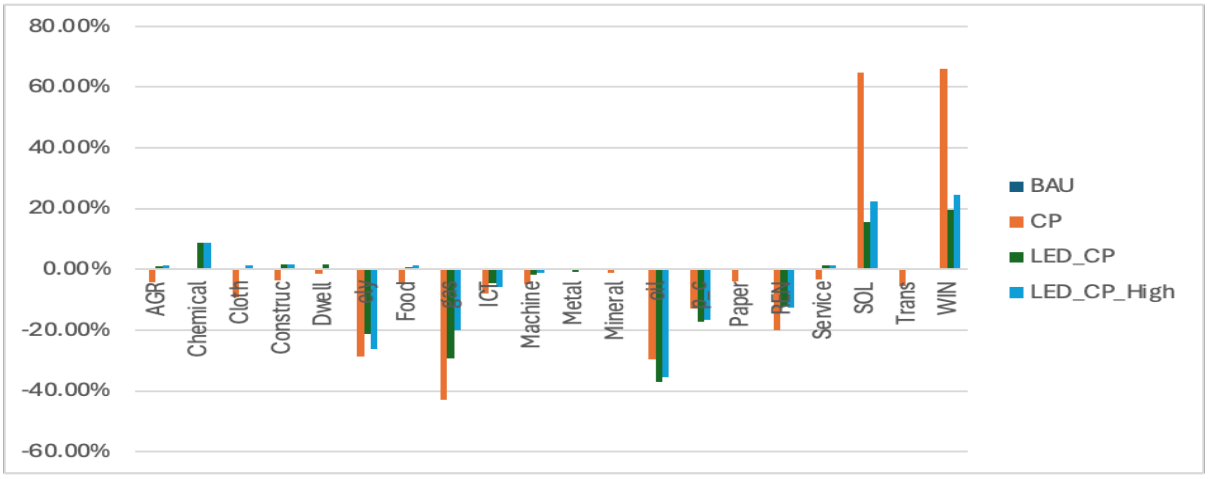
In Korea, the changes in real GDP are relatively small even after achieving the mitigation target of the CP scenario. Real GDP in the CP scenario decreases by less than 4% compared to the BAU scenario. The country already reaches its carbon price of $400 per tCO2 in 2050 under the BAU scenario and also utilizes carbon capture options after the carbon price exceeds the cost of carbon capture options. Therefore, the negative economic impacts under the CP scenario (compared to BAU) do not appear to be large. Some LED measures included in this model, such as energy efficiency improvements, may have positive economic effects under the LED_CP and LED_CP_High scenarios.

Figure 23. Changes in real GDP in Korea (2022-2050) (% difference from BAU)



The following figure shows the changes in sectoral production in Korea (2022-2050). The sectoral production (2022-2050) relative to BAU shows a similar trend to global production, with a significant decrease in production of fossil fuels and non-renewable electricity and a substantial increase in solar and wind power.

Figure 24. Changes in sectoral production (without carbon capture) (2022-2050) in Korea (% difference from BAU)



For the carbon capture in Korea, the result shows that the utilization of carbon capture increases significantly from the 2040s, when carbon prices rise sufficiently. In the CP scenario, the utilization of carbon capture reaches about 70.65 MtCO2, which is a slightly lower than the carbon capture dependency considered in the 2050 carbon neutrality scenario in Korea.

In the LED_CP scenario, the dependence on carbon capture increases slightly, unlike the global case, but in the LED_CP_High scenario, the dependence of carbon capture is lower than in the CP and LED_CP scenarios, as in the global case. Compared to other developed countries, the cost of carbon capture is relatively high, indicating that the utilization of carbon capture in the BAU scenario remains very low. In 2050, however, the reliance on carbon capture to meet mitigation targets increases.

Figure 25. Carbon Capture in Korea by scenario (unit: MtCO2)

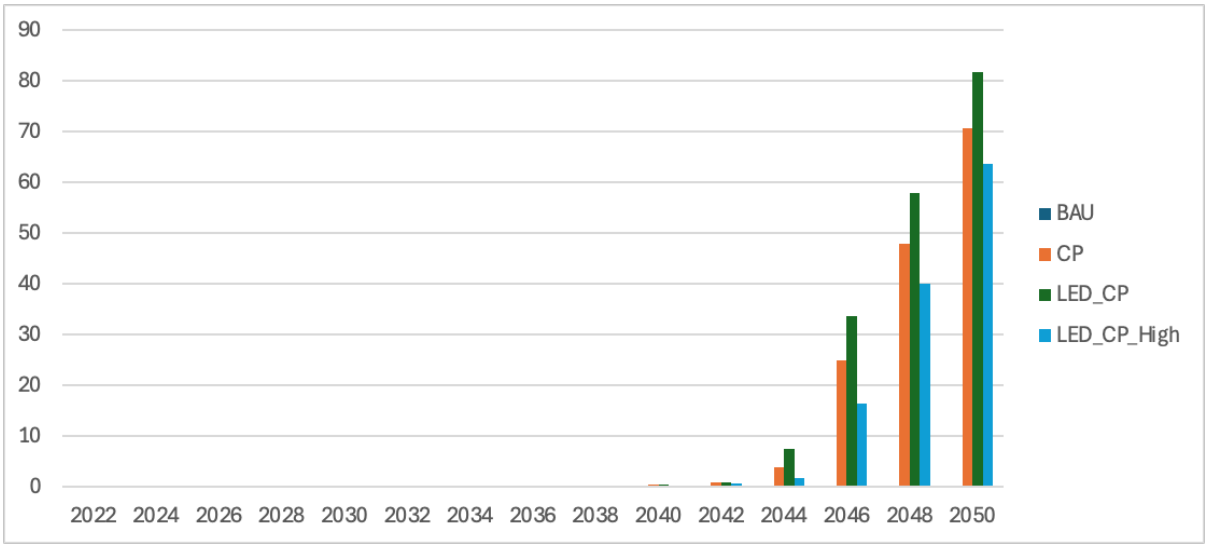
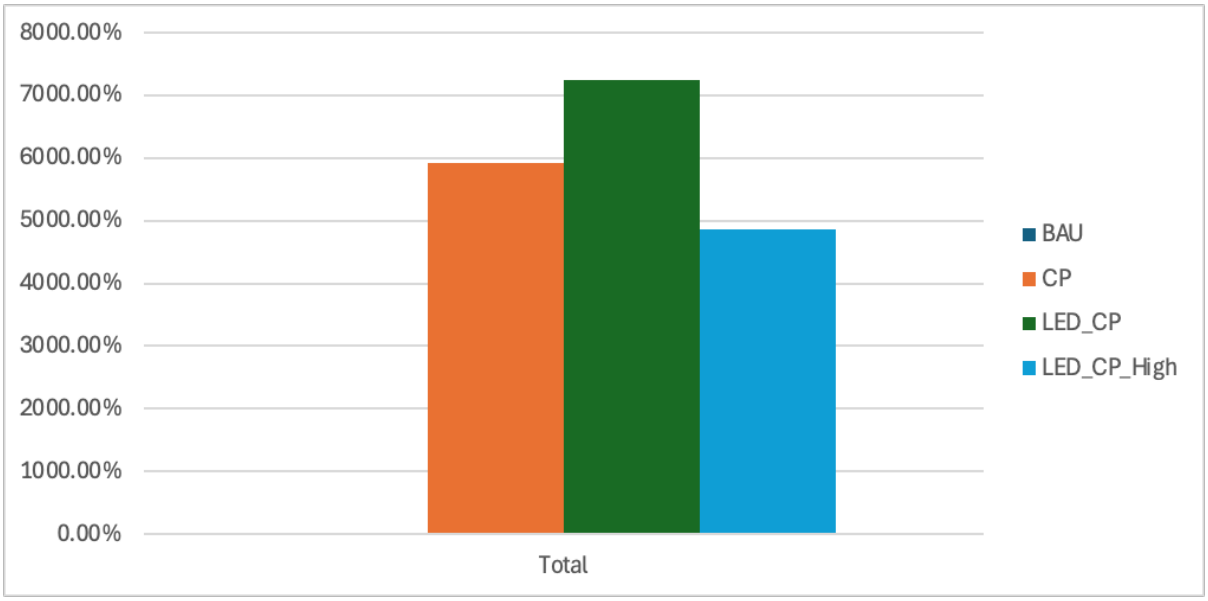


Figure 26. Changes in Carbon Capture (2022-2050) (% difference from BAU)



2.8. Conclusion

In this study, the UNICON-G-CGE with CCS model was used to analyze the impact of some LED measures, such as improving energy efficiency, reducing household energy consumption, and increasing energy-related elasticities of substitution, on reducing dependence on carbon capture. As there is no carbon capture sector in the existing GTAP 11 database, the study added a new sector for the analysis. The analysis was conducted by reflecting the current policy and the below 2-degree scenarios of the NGFS, and the global and Korean cases were analyzed. As mentioned earlier, the LED measures consist of the LED_CP scenario, which applies improvements in energy efficiency and reductions in household energy consumption, and the LED_CP_High scenario, which additionally reflects higher energy-related elasticities of substitution. In the CGE model, energy efficiency improvements are shown to have some rebound effect, but at the same time they also have a positive economic effect by increasing productivity and making energy sources relatively less expensive.

In global cases, the carbon price to achieve a below 2-degree pathway appears to significantly reduce final energy demand and also causes some loss in global real GDP. It also shows a significant reduction in fossil fuel and non-renewable electricity production. Carbon capture is expected to increase rapidly from the mid-2030s. Although carbon capture is significantly expanded in the LED_CP and LED_CP_High scenarios, it is shown that 2.8% to 9.4% less reliance on carbon capture is required compared to the CP scenario. The results

suggest that low demand measures can alleviate the reliance on carbon capture to meet mitigation targets. In addition, carbon capture can have some effect in reducing the burden of greenhouse gas reduction, limiting the increase in the economy-wide carbon price and limiting the real GDP losses. Similar results can be seen in the case of the Republic of Korea. Korea faces a shortage of domestic carbon capture and storage and is considering expanding overseas storage. The cost of carbon capture in Korea in this study is relatively higher than in other developed countries. It therefore shows that the deployment of carbon capture is increasing at a relatively late stage compared to other developed regions. In the LED_CP_High scenario, the reliance on carbon capture is lower than in the other scenarios, indicating that LED measures can contribute to reducing the reliance on carbon capture.

However, there are limitations to this study. First, the study is currently in the pilot stage as it requires adding a new sector with significant techno-economic uncertainties to the global GTAP dataset. There is no carbon capture sector in the GTAP 11 database, so the study added a reference carbon capture sector based on literature and previous studies. However, the economic and technical information is quite limited and there are significant uncertainties. In addition, there are various carbon capture technology options, and the input structure and costs can vary substantially by region and sector; however, the study initially considered one carbon capture technology. The potential for regional carbon capture storage, which may act as a constraint, was also not included in the model. In addition, the study currently includes limited low energy demand measures, which need to be expanded in further research. Also, the study considered autonomous energy efficiency improvement exogenously, so it has the limitation that it does not consider the costs required to achieve the energy efficiency. Despite such limitations, the contributions of the study include that carbon capture technology can act as a backstop technology to limit the increase in economy-wide carbon prices and support the achievement of mitigation targets. At the same time, the study shows some potential for some LED measures to reduce reliance on carbon capture to meet mitigation targets. Further research could improve the study by considering additional LED measures, including the circular economy in industry, and various types of technology options, including different CCS/DAC options and hydrogen.

3. Impacts of Production-based and Consumption-based carbon pricing in LEDS

3.1. Introduction

Carbon pricing internalizes the external costs of greenhouse gas (GHG) emissions, such as health impacts and property damage, by attaching a price to CO_2 emissions. This mechanism shifts the burden of climate damage onto emitters, encouraging them to either reduce their emissions or pay for them. Rather than mandating specific reductions, it provides economic incentives for cleaner development, ensuring flexibility and minimizing costs. By setting an adequate price on emissions, carbon pricing drives investment in low-carbon technologies and innovation, supporting sustainable economic growth.

Carbon pricing can be applied to different types of emissions, including direct and indirect emissions. GHG emissions are categorized into three scopes based on their source and level of control. Scope 1 covers direct emissions from owned or controlled sources, such as fuel combustion in company vehicles, industrial processes, and refrigerant leaks. Scope 2 includes indirect emissions from purchased electricity, steam, heating, and cooling that an organization consumes but does not generate. Scope 3 accounts for all other indirect emissions in the value chain, including upstream emissions from raw materials, supplier transportation, and business travel, as well as downstream emissions from product use and disposal.

Carbon regulation is increasingly shifting from production-based to consumption-based GHG accounting, recognizing emissions embedded in global supply chains. Policies such as the EU's Carbon Border Adjustment Mechanisms (CBAMs) impose carbon costs on imports to prevent carbon leakage and promote cleaner production. Governments are expanding Scope 3 emissions reporting and extended producer responsibility (EPR), holding companies accountable for emissions in their supply chains. Some regions are exploring carbon consumption taxes, integrating climate policies into trade agreements, and adjusting tariffs to favor low-carbon goods. Growing consumer and investor pressure is driving stricter ESG disclosure requirements and efforts to decarbonize the entire supply chain, supported by digital tracking tools such as blockchain and AI-based carbon footprint monitoring. As regulations and market forces converge, companies must address emissions across their entire value chain to ensure compliance and maintain a competitive advantage in a low-carbon economy.

The World Bank Carbon Pricing Leadership Coalition (2018) argues that pricing carbon consumption, rather than just production, can enhance the economic efficiency and

environmental effectiveness of carbon pricing schemes by ensuring that the costs of CO_2 emissions are fully passed through the entire value chain. A consumption-based carbon price mitigates the risk of cross-border carbon leakage and accounts for extraterritorial emissions, ensuring a level playing field for producers regardless of their jurisdiction. Several jurisdictions—including California, China, Tokyo, and South Korea—already operate carbon pricing systems that regulate the consumption of CO_2 emissions associated with electricity and fuels, providing valuable policy insights.

However, a comprehensive quantitative evaluation of consumption-based carbon pricing is still lacking a rigorous scientific assessment. Without a thorough economic evaluation, the risk of policy failure and unintended economic or environmental consequences remains. Therefore, a detailed examination of the economic impacts of consumption-based carbon pricing is essential, and this study aims to bridge the gap between research and practice.

3.2. Literature Review

As mentioned above, while the concept of consumption-based emissions and carbon pricing can provide various policy insights, there is limited research on consumption-based and production-based emissions. Karakaya et al. (2019) emphasize that the existing research on emissions and climate policy has largely focused on production-based accounting systems, which may obscure the real drivers of emissions. This study analyzed the convergence of production-based and consumption-based emissions data in 35 Annex B countries from 1990 to 2015. While the study found convergence in per capita emissions based on production-based emissions accounting, it found no convergence in consumption-based emissions. The study raised concerns about analyzing emissions and economic growth based on production-based emissions accounting, which does not take into account trade perspectives. The study found some evidence that carbon leakage contributed to the decoupling of economic growth and production-based emissions in Annex B countries. It emphasizes the importance of considering consumption-based emissions in understanding emission patterns and providing policy insights for dealing with emissions from outside the country.

Wang et al. (2024) analyzed the peak of consumption-based CO2 emissions. The study calculated the consumption-based CO2 emissions of countries (1990-2016) by utilizing an environmentally extended multi-regional input-output model and applied factor decomposition analysis of domestic and foreign emissions. The study found that all developed countries have reached a peak in consumption-based emissions, with most countries peaking between 2003

and 2008. However, the study found evidence of divergence between domestic and foreign emissions across countries. Six developed countries showed that foreign emissions exceeded domestic emissions, and five countries indicated an increasing trend of foreign emissions towards domestic emissions. The structural decomposition analysis suggested that the key driving forces of reducing foreign emissions in 16 developed countries include foreign carbon intensity and total input structure, and those of reducing domestic emissions include domestic carbon intensity and per capita final demand. Mangir and Sahin (2022) utilized environmentally extended global multi-regional input-output (EE GMRIO) and calculated Turkey's consumption-based accounting emissions. The study questioned the adequacy of production-based accounting of GHG emissions, which could lead to carbon leakage. It found that Turkey was a net importer of emissions, that about 10% of its consumption-based emissions occurred abroad, and that sectoral contributions differed significantly between production-based and consumption-based frameworks. This research suggests that consumption-based emissions can provide comprehensive inputs for climate change mitigation policies. While there are some studies that draw academic and policy implications based on a comparison of production- and consumption-based emissions, there are very limited studies that provide a comprehensive assessment of consumption-based carbon pricing.

3.3. Data and Methods

GTAP11 is a global trade database that offers sectoral emissions intensity estimates, compiled from national input-output tables and global trade data. It provides global input-output transaction data for the base year of 2017.

The GTAP 11 database (Aguiar et al., 2022) of August 2023 includes expanded regional coverage of 141 countries and 19 aggregate regions and 65 products and services. For the purposes of this study, the data from 160 countries and aggregate regions are consolidated into 7 distinct regions, as shown in [Table 1]. With a special focus on the Asian developing countries, the study uses the Asian Development Bank (ADB)'s regional classification to sort the Asian countries and uniquely identifies Korea as a separate region.

Table 10. Regional Classification

Label	Description
KOR	Republic of Korea

OECD	Organisation for Economic Co-operation and Development (except the Republic of Korea): Europe region (European Union member countries, rest of Europe, rest of European Free Trade Association, and United Kingdom) + Australia, Canada, New Zealand, and United States, Japan
CCA	Caucasus and Central Asia
EAsia	East Asia: Taipei,China, Mongolia, Democratic People's Republic of Korea, Macao Special Administrative Region, China
SAsia	South Asia: Bangladesh, India, Nepal, Pakistan, and nearby countries (Afghanistan, Bhutan, Maldives, and Sri Lanka)
SEAsia	Southeast Asia: 10 Association of Southeast Asian Nations members and Timor-Leste
DC	The other developing economies: Countries not included in OECD and five Asian subregions

The study aggregates 65 sectors into 20 sectors. Major energy commodities, such as coal, oil, and gas, are identified separately. The sector classification adopted in this study is as follows:

Table 11. Sector Classification

Sector	Label	GTAP Code
Coal	COA	COA
Oil	OIL	OIL
Gas	GAS	GAS
Electricity	ELY	ELY
Gas manufacture and distribution	GDT	GDT
Petroleum and Coal Products	P_C	P_C
Agriculture	AGR	PDR, WHT, GRO, V_F, OSD, C_B, PFB, OCR, CTL, OAP, RMK, WOL, FRS, FSH
Mineral	Mineral	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	ELE, EEQ
Vehicle	Vehicle	MVH, OTN
Machine	Machine	OME, OMF
Construction	Construc	CNS

Service	Service	OSG, EDU, HHT, WTR, AFS, TRD, WHS, CMN, OFI, INS, RSA, OBS, ROS
Transport	Trans	OTP, WTP, ATP
Dwellings	Dwell	Dwell

3.3.1. Carbon Emissions Accounting Approach

Production-based emissions (direct emissions) for sector *i*, emission source *j*, or region *r* are calculated using equation (1). $\boldsymbol{P}^{j,i,r}_{production}$ is a matrix of production-based emissions by emission source, sector, and region, and eco^{r}_{ji} indicates the CO_2 emissions of sector *i* coming from emission source *j*.

$$\boldsymbol{P}^{j,i,r}_{Production} = eco^{r}_{ji} \quad (1)$$

There are several methods for estimating consumption-based emissions (all emissions along the global value chain), such as the Multi-Regional Input-Output (MRIO) method and the Emissions Embedded in Bilateral Trade (EEBT) method. The MRIO method partitions trade, and therefore emissions, associated with intermediate consumption and final consumption; the EEBT method combines both intermediate and final consumption as final demand, without accounting for trade flows through multi-country supply chains (Peters, 2008; Peters et al., 2011). In other words, the two methods estimate the same total global carbon emissions, but differ in how they each allocate intermediate consumption in international trade (Peters et al., 2011). While the MRIO method may provide a more detailed decomposition of carbon emissions associated with international trade, realistically, it is extremely difficult to isolate and comprehensively track how intermediate consumption flows in complex global value chains (Peters, 2008).

Therefore, we utilize the EEBT method to calculate consumption-based carbon emissions. Following Peters et al. (2011), we first calculate the total output x of region *r*, as seen below in equation (2), where $\boldsymbol{Z}^{rs}$ and $\boldsymbol{y}^{rs}$ indicate intermediate inputs, supplied by region *r*, for production and final demand of region *s*, respectively. Using the above total outputs and intermediate inputs, we can calculate an input coefficient $\alpha^{rs}_{ij} = Z^{rs}_{ij}/x_i$, the amount of intermediate input per unit of total output. Using this input coefficient and applying the concept of the Leontief inverse per customary input-output analysis procedures, equation (2) can be rewritten into equation (3).

$$\boldsymbol{x}^r = \boldsymbol{Z}^{rr}\mathbf{1} + \boldsymbol{y}^{rr} + \sum_s(\boldsymbol{Z}^{rs}\mathbf{1} + \boldsymbol{y}^{rs}) \quad (2)$$

$$\boldsymbol{x}^r = (\boldsymbol{I} - \boldsymbol{A}^{rr})^{-1}\{\boldsymbol{y}^{rr} + \sum_s(\boldsymbol{Z}^{rs} + \boldsymbol{y}^{rs})\} \quad (3)$$

Finally, we calculate the consumption-based emissions embodied in bilateral trade by multiplying the carbon intensity of sector *i* in region *r*, $f_i^r = p_i^r / x_i^r$, to equation (4).

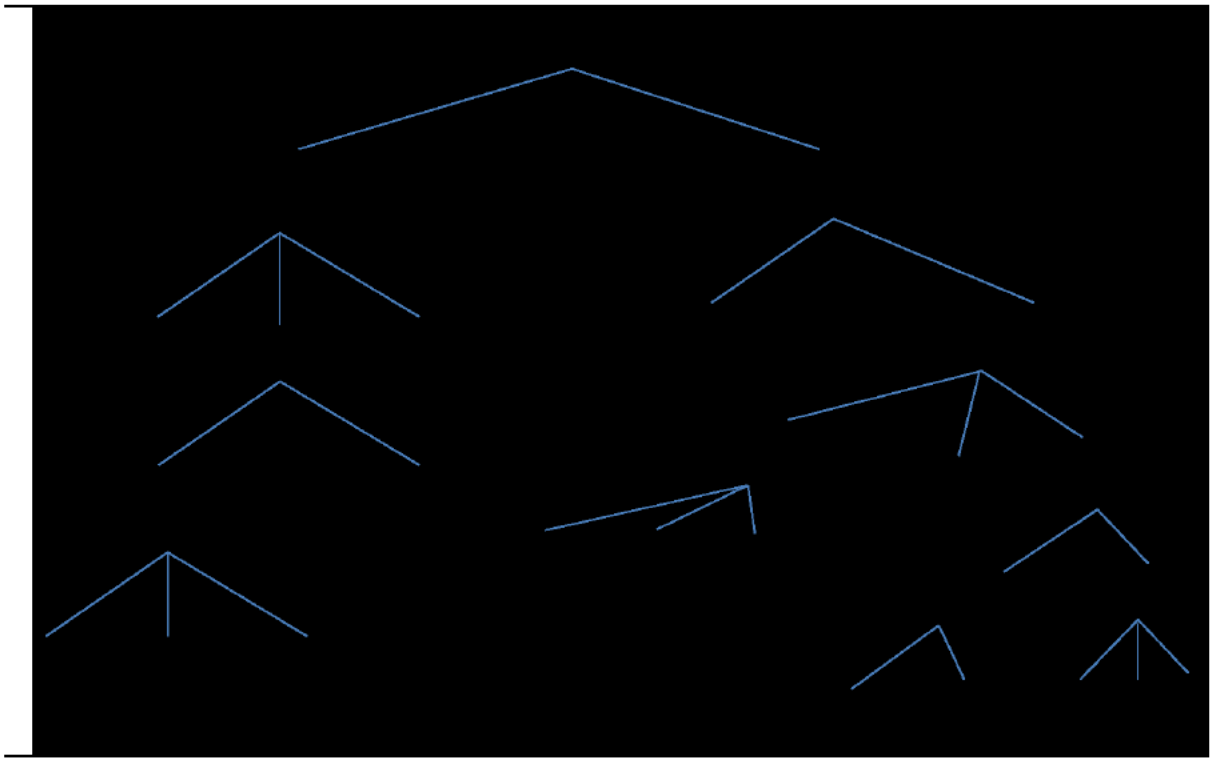
$$\boldsymbol{P}_{scope3}^r = \boldsymbol{f}^r \times (\boldsymbol{I} - \boldsymbol{A}^{rr})^{-1} \times \boldsymbol{y}^{rr} + \sum_s\{f^s \times (1 - A^{ss})^{-1} \times \sum_s(\boldsymbol{Z}^{sr}\mathbf{1} + \boldsymbol{y}^{sr})\} \quad (5)$$

All calculations and estimations were conducted using the General Algebraic Modeling System (GAMS), release 36.2.0.

3.3.2. Structure of the CGE Model

The nesting structure and the key parameters of the CGE model for consumption and production based emissions are as follows.

Figure 27. Nesting Structure



Source: Author's own elaboration.

Table 12: 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
Substitution between KTR bundle and energy	σ^r	0.5
Substitution between capital, land, and natural resources	σ^k	0
Substitution between electricity and fossil fuel	σ^e	0.5
Substitution between renewable and non-renewable electricity	σ^l	1
Substitution between fossil energies	σ^f	1
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	1.5
Substitution between capital, land, and natural resources	σ^k	0.2
Substitution between electricity and fossil fuel	σ^e	4
Substitution between renewable and nonrenewable electricity	σ^l	4
Substitution between fossil energies	σ^f	1

GTAP = Global Trade Analysis Project, KTR = Capital-Land-Natural Resource, KTRE = Capital-Land-Natural Resource-Energy.
Source(s): Author's own elaboration.

3.3.3. Scenario

We design three scenarios to analyze the effects of production-based versus consumption-based carbon pricing. The 'BAU' (Business-As-Usual) scenario represents a baseline projection of the global economy without additional carbon pricing policies. Two policy scenarios are introduced to examine the impacts of carbon pricing on production- and consumption-based emissions. The first policy scenario, 'CP' (Carbon Pricing on Direct Emissions), applies a tax on direct carbon emissions. The second policy scenario, 'CBE' (Carbon Pricing on Consumption-Based Emissions), imposes a tax on emissions embedded in all consumed commodities, including those used for intermediate and final demand.

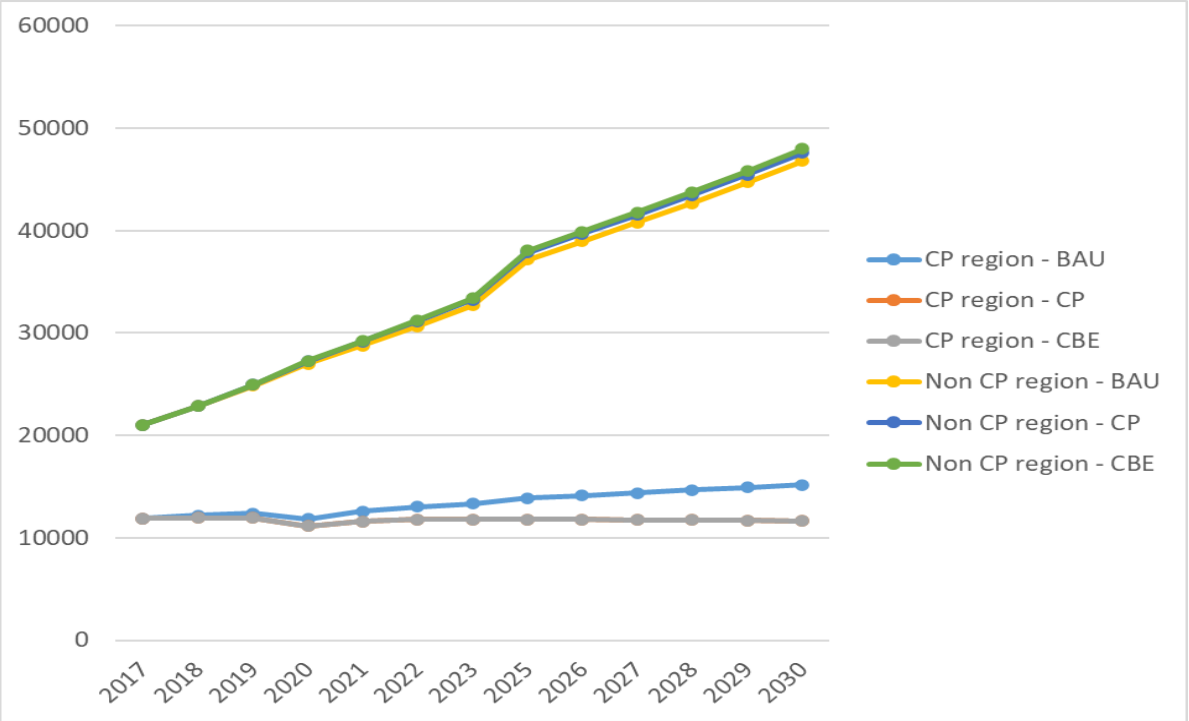
Under the CP scenario, all direct emissions from intermediate and final demand for commodities are taxed. In contrast, under the CBE scenario, emissions embedded in all consumed commodities are subject to taxation. Half of the carbon pricing revenue is assumed to be recycled to reduce labor taxes, while the remaining half is transferred to households as a lump-sum payment.

To ensure a fair comparison between the two policy scenarios, we assume an identical emissions reduction target—an additional 2% annual reduction from BAU emissions levels. In addition, carbon pricing is applied only to a subset of the global economy rather than globally, allowing us to assess interactions between regulated and unregulated regions, such as carbon leakage and trade competition. Specifically, carbon pricing is only implemented in OECD countries and South Korea (KOR), referred to as the 'CP region' (regions with carbon pricing). The rest of the world, which consists of relatively less developed economies, is referred to as the 'Non-CP region' (regions without carbon pricing).

3.4. Result and Discussion

The figure below illustrates the CO_2 emission trajectories for the two aggregated regions under the three scenarios. As expected, in the carbon pricing scenarios (CP and CBE), emissions in the regulated region (CP region) decrease as a result of policy intervention. From 2018 onwards, emissions in the CP region are constrained by an additional 2% reduction per year below BAU, which accumulates over time in both the CP and CBE scenarios. Consequently, emissions are reduced by 2% in 2018, 3.96% in 2019, 5.88% in 2020, and so on, with reductions increasing each year. By 2030, total emissions are 23.1% lower than in the BAU scenario.

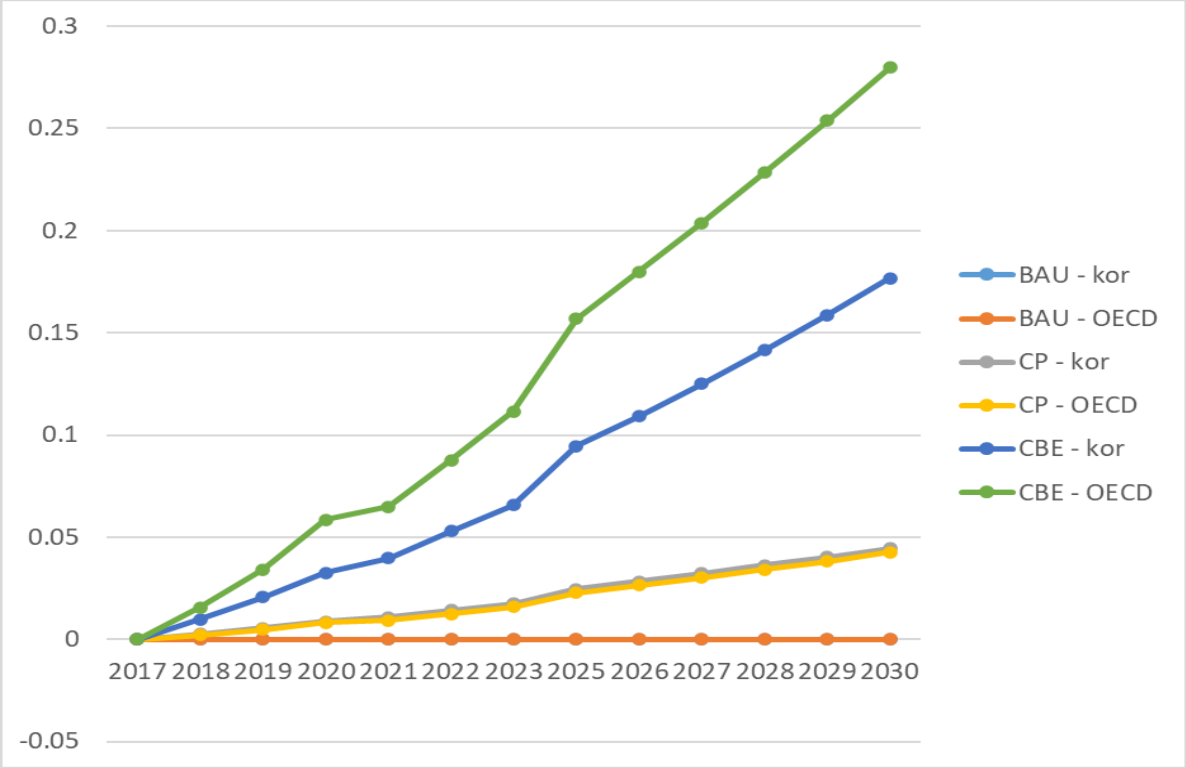
Figure 28. Regional CO2 emissions by Scenarios (Unit: MtCO2)



The following figure illustrates the carbon price levels required to achieve the emission reduction targets in the OECD and Korea under both carbon pricing approaches. Although the reduction targets (in terms of percentage decrease from BAU) are identical for both regions, the carbon price required to meet these targets varies significantly between policy types and regions.

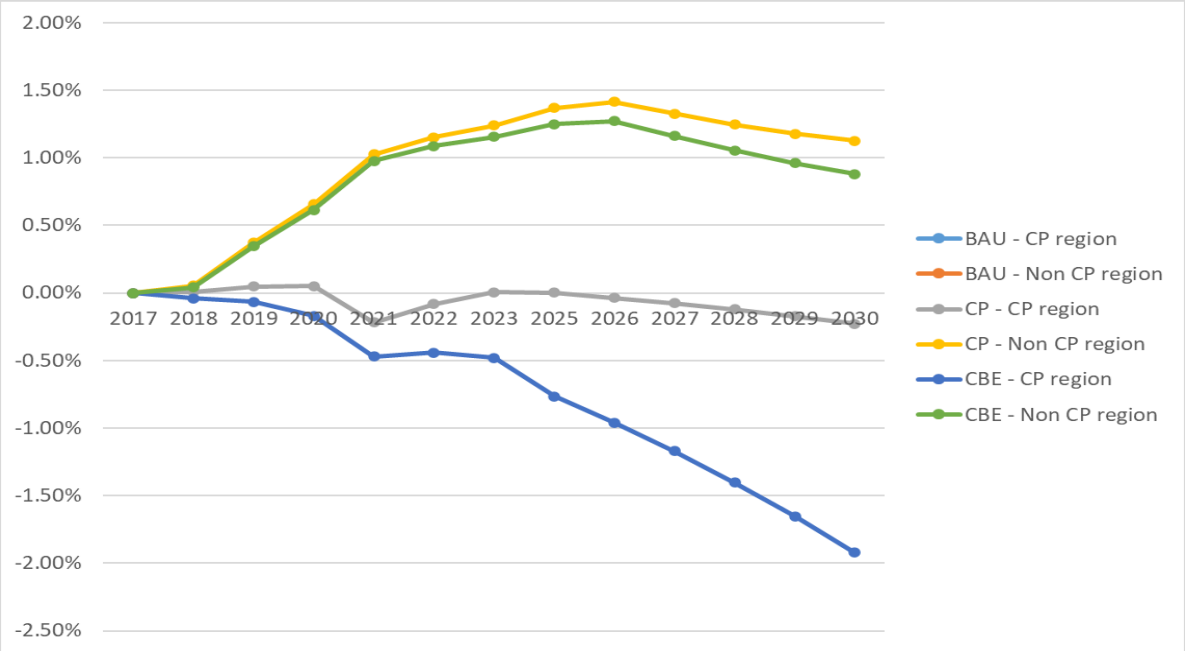
The carbon price required for the CP scenario (production-based pricing) is relatively moderate, reaching 44.6 USD per ton of CO_2 in Korea and 42.6 USD in the OECD by 2030. However, the CBE scenario (consumption-based pricing) requires a much higher carbon price—176.6 USD in Korea and 279.7 USD in the OECD by 2030. This means that the carbon price needed to meet the same reduction targets is nearly four times higher (3.96x) in Korea and 6.57 times higher in the OECD under consumption-based pricing. These results indicate that consumption-based emissions regulations are significantly more difficult to implement compared to production-based pricing.

Figure 29. Carbon price required for meeting emission targets (Unit: 1,000 USD/tCO2)



The economic impact of carbon pricing is closely related to the level of carbon prices. The figure below shows a modest impact of carbon regulation on real GDP for the case of production-based carbon pricing, reaching only -0.23% in 2030 in the CP region, while it is quite significant for consumption-based carbon pricing, reaching down to -1.92%. The consumption-based carbon pricing results in a substantial burden on the economy to meet a reduction commitment. The unregulated region enjoys an economic gain from regulation by the others, with real GDP higher by 0.88 to 1.13% relative to BAU. It is interesting to note that under the production-based carbon pricing of OECD and Korea, total global GDP grows higher by 0.47% above BAU. The global GDP gain becomes negative by -0.48% under the consumption-based carbon pricing, although it increases to 0.28% by 2023 and then after declines.

Figure 30. Real GDP impacts by Scenarios (% change relative to BAU)



The following figure shows the changes in emissions in unregulated regions, indicating carbon leakage. It is interesting to see that carbon leakage is higher with consumption-based carbon pricing than with that with production-based. Consumption-based carbon pricing promotes the unregulated region to increase emissions more and grow economically faster than the production-based carbon pricing.

Figure 31. CO2 emissions of non-regulated region (% change from BAU)

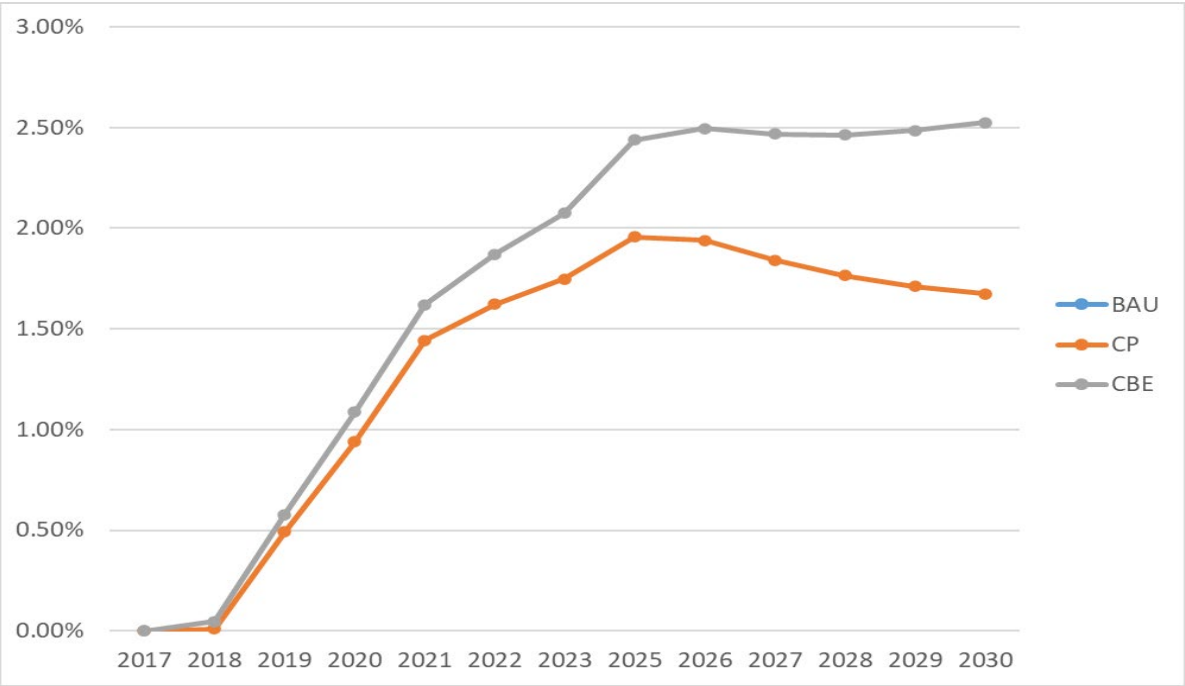
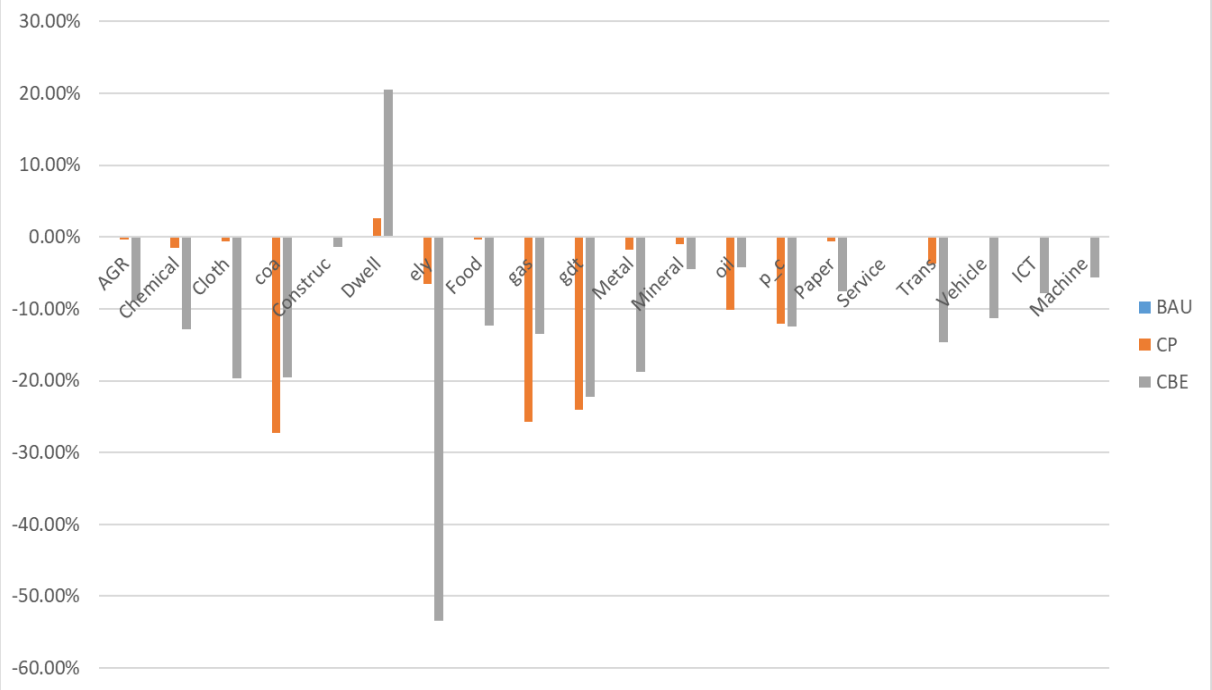


Figure 32. Sectoral output impacts from carbon pricing (% change from BAU)



The figure above shows the different impacts of production- and consumption-based carbon pricing on individual sectors. Most of the manufacturing and service industries, except dwelling, face substantial contractions under the consumption-based carbon pricing, while the fossil fuel production industries bear the most of negative impacts under the production-based carbon pricing.

3.5. Conclusion

Consumption-based emissions regulation has become increasingly popular in environmental regulation, such as climate change mitigation. Recently, Scope 2 and Scope 3 emissions have been subject to disclosure requirements and carbon market regulation. Scope 3 GHG emissions are a type of consumption-based emissions, athough there are some differences depending on how they are defined. However, the economic and environmental impacts of consumption-based emissions regulations have not yet been fully scrutinized with rigorous economic modeling.

This study evaluates the economic and climate impacts of consumption-based carbon pricing, with a particular focus on how it compares to conventional production-based carbon

pricing. Using dynamic multi-regional CGE modeling, we find that consumption-based carbon pricing results in a higher carbon price, a greater loss of economic output, and greater emissions leakage to outside economies. Most manufacturing and service industries, except dwelling, face substantial contractions under consumption-based carbon pricing, while fossil fuel production industries bear most of the negative impacts under production-based carbon pricing.

A fundamental reason for the higher economic burden of consumption-based carbon regulation is its limited ability to incentivize the substitution between clean and dirty energy sources. One of the most effective ways to reduce emissions is to shift from high carbon energy sources, such as coal, oil, and gas, to low or zero carbon alternatives, such as renewables and nuclear energy. This transition is better facilitated putting a carbon price on direct emissions rather than on embedded carbon. As fossil fuels such as coal and gas produce high direct emissions but relatively low embodied emissions, consumption-based carbon pricing has limited effectiveness in driving fuel switching behavior. As a result, consumption-based carbon pricing alone has only a marginal role in supporting the transition to a low-carbon economy, and can at best serve as a complementary measure alongside production-based carbon regulation.

The findings of this study highlight the need for a broader range of scenario analyses to fully assess the economic and environmental implications of consumption-based carbon pricing. Future research should explore the potential synergies and trade-offs between production- and consumption-based carbon regulations through more in-depth analyses using diverse methodologies, including general equilibrium modeling, empirical analyses, and game-theoretic mechanism design.

4. Conclusion

In exploring the potential of LEDS, the study examined (1) the potential of LEDS for reducing dependence on CCS in achieving net zero and (2) the impact of production- and consumption-based carbon pricing in LEDS.

First, the LEDS scenario is known to have the effect of reducing the dependence on supply-side options, such as CCS in the low-carbon transition process. In this study, the UNICON-G-CGE with CCS model was developed and utilized to analyze this potential, with the new inclusion of carbon capture/dac, a backstop technology not included in the GTAP 11 database. The input cost structure, cost components, and sectoral utilization were configured based on previous research. Four scenarios were established in the study. In addition to the BAU and CP scnearios, which follow the emissions pathways of the NGFS Current Policy and the below 2-degree scenario, the LED scenario reflects improvements in energy efficiency and reductions in household energy consumption in addition to the CP scenario. Finally, the LED_CP_High scenario increases the elasticity of substitution of energy sources to enable rapid changes in the production structure of industries in response to price changes. The model shows that the CCS component acts as a backstop technology, preventing the economy-wide carbon price from rising too much. It also shows that when carbon prices are reflected to achieve emissions reductions, real GDP can be reduced, but if LED measures are included, this can have a positive economic impact. It also shows that LED measures can support abatement, reducing the reliance on CCS to achieve the same level of emission reductions. The case of Korea appears to be generally similar to the global case, but it has been shown that the reliance on CCS can be reduced by including up to LED_CP_High measures. As a result, it provides some evidence that the reliance on CCS can be reduced to some extent by including LED measures. However, there are limitations that need to be updated in future research. CCS technology has not yet been considered in detail for each sector, and in this study it has been included as a single high-cost technology, thus results are limited. This will need to be supplemented in future research, and we will carry out further research in the future as hydrogen and other factors have not been considered.

Next, the study analyzed the impact of production-based and consumption-based carbon pricing on LEDS. The UNICON-G-CGE model based on the GTAP 11 database was utilized, and countries were classified using the ADB regional classification. To distinguish between production-based and consumption-based emissions, consumption-based emissions were calculated using the Emissions Embedded in Bilateral Trade (EEBT) method. The

scenarios analyzed consisted of a BAU scenario without additional carbon price, a CP scenario for direct carbon emissions, and lastly a CBE scenario that taxes emissions for all consumed commodities. In addition, carbon pricing to achieve emission mitigations was only introduced in the OECD and South Korea to examine carbon leakage, and was not imposed on the other regions. Looking at the carbon prices required for the OECD and Korea to achieve their reduction targets, it was found that a higher level of carbon pricing is required in the CBE scenario than in the CP scenario. This means that regulating consumption-based emissions is more difficult to implement than production-based emissions. In terms of carbon leakage, it is interesting to note that consumption-based carbon pricing leads to greater carbon leakage than production-based carbon pricing. Consumption-based carbon pricing promotes the unregulated region to increase emissions more and grow economically faster than the production-based carbon pricing. A reason for the high economic burden of consumption-based regulation is the limited incentives for the clean energy transition. One of the most effective ways to encourage a shift from carbon-intensive to alternative energy sources is through direct carbon pricing. Of course, consumption-based carbon regulation can play a complementary role, but it is likely to be limited. Future research should explore in depth the synergies and conflicts between production- and consumption-based carbon regulation in depth through various models.

5. References

Aguiar, A., Chepeliev, M., Corong, E., & van der Mensbrugghe, D. (2023). The Global Trade Analysis Project (GTAP) Data Base: Version 11. Journal of Global Economic Analysis,7(2). https://doi.org/10.21642/JGEA.070201AF

Andrew, R. M., & Peters, G. P. (2013). A Multi-Region Input–Output Table Based on the Global Trade Analysis Project Database (GTAP-MRIO). *Economic Systems Research*, 25(1), 99–121. https://doi.org/10.1080/09535314.2012.761953

Andrew, R., Peters, G. P., & Lennox, J. (2009). Approximation and Regional Aggregation in Multi-Regional Input–Output Analysis for National Carbon Footprint Accounting. *Economic Systems Research*, 21(3), 311–335. https://doi.org/10.1080/09535310903541751

Arto, I., Rueda-Cantuche, J. M., & Peters, G. P. (2014). Comparing the GTAP-MRIO and WIOD Databases for Carbon Footprint Analysis. *Economic Systems Research*, 26(3), 327–353. https://doi.org/10.1080/09535314.2014.939949

Barrett, J., Peters, G., Wiedmann, T., Scott, K., Lenzen, M., Roelich, K., & Le Quéré, C. (2013). Consumption-based GHG emission accounting: A UK case study. *Climate Policy*, 13(4), 451–470. https://doi.org/10.1080/14693062.2013.788858

Barrett, J., Pye, S., Betts-Davies, S., Broad, O., Price, J., Eyre, N., Anable, J., Brand, C., Bennett, G., Bennett, G., Carr-Whitworth, R., Garvey, A., Giesekam, J., Marsden, G., Norma, J., Oreszczyn, T., Ruyssevelt, P., & Scott, K. (2022). Energy demand reduction options for meeting national zero-emission targets in the United Kingdom. *Nature Energy. 7.* 726-735.

Bukar, A. M., & Asia, M. (2024). Technology readiness level assessment of carbon capture and storage technologies, *Renewable and Sustaianble Energy Reviews, 200,* 114578

Energy Research Institute for ASEAN and East Asia. (2022). Study on the Potential for Promoting Carbon Dioxide Capture, Utilisation, and Storage (CCUS) in ASEAN Countries (Vol. II). ERIA

Giljum, S., Wieland, H., Lutter, S., Eisenmenger, N., Schandl, H., & Owen, A. (2019). The impacts of data deviations between MRIO models on material footprints: A comparison of EXIOBASE, Eora, and ICIO. *Journal of Industrial Ecology*, 23(4), 946–958. https://doi.org/10.1111/jiec.12833

Global CCS Institute. (2025). Facilities Database. CO2RE Homepage. https://co2re.co/facilitydata. Accessed on February 10, 2025.

Grant, N., Hawkes, A., Napp, T., & Gambhir, A. (2021). Cost reductions in renewables can substantially erode the value of carbon capture and storage in mitigation pathways. *One Earth, 4*(11), 1588-1601. https://doi.org/10.1016/j.oneear.2021.10.024

Hilaire, J., Minx, J. C., Callaghan, M. W., Edmonds, J., Luderer, G., Nemet, G. F., Rogelj, J., & del Mar Zamora, M. (2019). Negative emissions and international climate goals—learning from and about mitigation scenarios. *Climatic Change, 157*, 189-219. https://doi.org/10.1007/s10584-019-02516-4

Huenteler, J., Niebuhr, C., & Schmidt, T. S.(2016). The effect of local and global learning on the cost of renewable energy in developing countries. *Journal of Cleaner Production. 128*. 6-21.

Inomata, S., & Owen, A. (2014). Comparative Evaluation of MRIO Databases. *Economic Systems Research*, 26(3), 239–244. https://doi.org/10.1080/09535314.2014.940856

International Energy Agency. (2020). CCUS in clean energy transitions: CCUS technology innovation. https://www.iea.org/reports/ccus-in-clean-energy-transitions/ccus-technology-innovation

International Energy Agency. (2024). Operating and planned CO2 capture capacity by application, Q1 2024 vs. 2030. https://www.iea.org/data-and-statistics/charts/operating-and-planned-co2-capture-capacity-by-application-q1-2024-vs-2030

Jung, T., Kim, Y-G., & Moon, J. (2021). The impact of demographic changes on CO2 emission profiles: Cases of East Asian countries. *Sustainability. 13*(2). 677.

Karakaya, E., Yilmaz, B., & Alatas, S. (2019). How production-based and consumption-based emissions accounting systems change climate policy analysis: the case of CO2 convergence. *Environmental Science and Pollution Research. 26.* 16682-16694.

Khanna, N. Z., Zhang, J., Lu, H., Feng, W., Johnson-Wang, M., & Zhou, N. (2023). Conceptualizing demand-side technological and social innovations in modeling pathways to carbon neutrality. *Energy Research & Social Science. 100.* 103115.

Lebling, K., Leslie-Bole, H., Byrum, Z., & Bridgwater, L. (2022, May 2). 6 things to know about direct air capture. World Resources Institute.https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal

Leeson, D., Mac Dowell, N., Shah, N., Petit, C., & Fennell, P. S. (2017). A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *International Journal of Greenhouse Gas Control, 61*, 71-84. https://doi.org/10.1016/j.ijggc.2017.03.020

Lenzen, M. (2011). Aggregation Versus Disaggregation in Input–Output Analysis of the Environment. *Economic Systems Research*, 23(1), 73–89. https://doi.org/10.1080/09535314.2010.548793

Lin, B.-Q., & Zhao, H.-S. (2023). Which sectors should be covered by the EU Carbon Border Adjustment Mechanism? Advances in Climate Change Research, 14(6), 952–962. https://doi.org/10.1016/j.accre.2023.11.012

Mangir, N., & Sahin, U. A. (2022). An environmentally extended global multi-regional input-output analysis of consumption-based and embodied import-based carbon emissions of Turkey. *Environmental Science and Pollution Research. 29.* 54813-54826.

Moran, D., & Wood, R. (2014). Convergence Between the Eora, WIOD, EXIOBASE, and OpenEU's Consumption-Based Carbon Accounts. *Economic Systems Research*. https://www.tandfonline.com/doi/abs/10.1080/09535314.2014.935298

Napp, T. A., Few, S., Sood, A., Bernie, D., Hawkes, A., & Gambhir, A. (2019). The role of advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budgets. *Applied Energy, 238*, 351-367. https://doi.org/10.1016/j.apenergy.2019.01.033

NREL. (2023). 2022 Cost of Wind Energy Review (NREL, December 2023). https://www.nrel.gov/docs/fy24osti/88335.pdf

OECD (2021), OECD Inter-Country Input-Output Database, http://oe.cd/icio

Owen, A. (2017). *Techniques for Evaluating the Differences in Multiregional Input-Output Databases: A Comparative Evaluation of CO2 Consumption-Based Accounts*. Springer.

Owen, A., Steen-Olsen, K., Barrett, J., Wiedmann, T., & Lenzen, M. (2014). A Structural Decomposition Approach to Comparing MRIO Databases. *Economic Systems Research*, 26(3), 262–283. https://doi.org/10.1080/09535314.2014.935299

Owen, A., Wood, R., Barrett, J., & Evans, A. (2016). Explaining value chain differences in MRIO databases through structural path decomposition. *Economic Systems Research*, 28(2), 243–272. https://doi.org/10.1080/09535314.2015.1135309

Perdana, S., & Vielle, M. (2022). Making the EU Carbon Border Adjustment Mechanism acceptable and climate friendly for least developed countries. *Energy Policy*, 170, 113245. https://doi.org/10.1016/j.enpol.2022.113245

Peters, G. P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics*, 65(1), 13–23. https://doi.org/10.1016/j.ecolecon.2007.10.014

Peters, G. P., & Solli, C. (2010). Global carbon footprints: Methods and import/export corrected results from the Nordic countries in global carbon footprint studies. Nordic Council of Ministers

Peters, G. P., Andrew, R., & Lennox, J. (2011). Constructing An Environmentally-Extended Multi-Regional Input–Output Table Using the GTAP Database. *Economic Systems Research*, 23(2), 131–152. https://doi.org/10.1080/09535314.2011.563234

Peters, G. P., Davis, S. J., & Andrew, R. (2012). A synthesis of carbon in international trade. *Biogeosciences*, 9(8), 3247–3276. https://doi.org/10.5194/bg-9-3247-2012

Rubin, E. S., Azevedo, I. M. L., Jaramillo, P., & Yeh, S. (2015). A review of learning rates of electricity supply technologies. *Energy Policy. 86*. 198-218.

Sendi, M., Bui, M., Mac Dowell, N., & Fennell, P. (2024). Geospatial techno-economic and environmental assessment of different energy options for solid sorvent direct air capture. *Cell Reports Sustainability. 1*(8). 100151.

Shuai, J., Wang, W., Liu, H., Huang, C., Yi, T., Zhao, Y., & Shuai, C. (2024). The impact of the EU's Carbon Border Adjustment Mechanism on the global iron and steel trade and emission reduction. *Environmental Science and Pollution Research*, 31(14), 21524–21544. https://doi.org/10.1007/s11356-024-32528-2

Sievert, K., Schmidt, T. S., & Steffe, B. (2024). Considering technology characteristics to project future costs of direct air capture. *Joule. 8*(4). 979-999.

SSP Scenario Explorer 3.1.0 (Release July 2024). https://data.ece.iiasa.ac.at/ssp/

Statista. (2025). Global CCS market size 2021-2031. https://www.statista.com/statistics/1044555/global-ccs-market-size/

Steen-Olsen, K., Owen, A., Hertwich, E. G., & Lenzen, M. (2014). Effects of Sector Aggregation on CO2 Multipliers in Multiregional Input–Output Analyses. *Economic Systems Research*, 26(3), 284–302. https://doi.org/10.1080/09535314.2014.934325

United Nations. (2024). United Nations Commodity Trade Statistics Database [dataset]. https://comtradeplus.un.org/TradeFlow

Wang, Z., Yan, H., Gao, X., Liang, Q., Mi, Z., & Liu, L. (2024). Have consumption-based CO2 emissions in developed countries peaked? *Energy Policy. 184.* 113894.

WEForum. (2023. Aug 9). Achieving net zero: Why costs of direct air capture need to drop for large-scale adoption. https://www.weforum.org/stories/2023/08/how-to-get-direct-air-capture-under-150-per-ton-to-meet-net-zero-goals/

Wiebe, K. S., & Lenzen, M. (2016). To RAS or not to RAS? What is the difference in outcomes in multi-regional input–output models? *Economic Systems Research*, 28(3), 383–402. https://doi.org/10.1080/09535314.2016.1192528

Wiedmann, T. (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecological Economics*, 69(2), 211–222. https://doi.org/10.1016/j.ecolecon.2009.08.026

World Bank Carbon Pricing Leadership Coalition, 2016. How can consumption-based carbon pricing address carbon leakage and competitiveness concerns? Executive Briefing.

Zhang, S., Bauer, N., Yin, G., and Xie, X. 2020. Technology learning and di usion at the global and local scales: A modeling exercise in the REMIND model. Technological Forecasting & Social Change. 151. 119765.

Zhao, L.-T., Chen, Z.-Y., Duan, Y.-X., & Qiu, R.-X. (2023). How will CBAM affect the decarbonisation of steel industry in China? A system dynamics approach. *International Journal of Production Research*, 1–22. https://doi.org/10.1080/00207543.2023.2285397

Quantifying minimum mobility needs: the Who, the Where and the Why

Marlin Arnz[1,2], Zakia Soomauroo[1,2], Vivien Fisch-Romito[3], Jihoon Min[4], Joel Millward-Hopkins[3], Paul Natsuo Kishimoto[4], Caroline Zimm[4], Benigna Boza-Kiss[4], and Bas van Ruijven[4]

[1]Reiner Lemoine Institute, Berlin, Germany
[2]Technical University Berlin, Germany
[3]University of Lausanne, Switzerland
[4]International Institute for Applied Systems Analysis (IIASA), Laxemburg, Austria

Abstract

Every individual worldwide should have the ability to move as they need without stressing the Earth's system limits. Currently, though, those conditions are not fulfilled, and there is no clear definition of what constitutes essential, sufficient, or minimum levels of mobility. We build upon established theories of fundamental human needs to clearly situate passenger trips within chains of provision and needs satisfaction to define "decent mobility". We propose a simple definition: an individual has decent mobility if they *can enact a set of trips that allows satisfaction of their fundamental needs within their resources and capabilities*. As such, decent mobility relates to i) individual capabilities and resources (time and monetary); ii) geography, environment, transport infrastructures, and built environment, determining mode availability and distances; iii) social and institutional phenomena that shape an individual's freedom. We also propose a quantification and operationalisation of decent mobility through personas with heterogenous needs, capabilities, and resources. Modelling these in different spatial contexts can reveal distributions of travel duration, distance, energy demand, emissions, and "decency" of the mobility provisioning system. Two case studies (Switzerland and Mauritius) showcase different modelling techniques and their (dis)advantages. In sum, this framework is useful to quantitatively evaluate today's and future transport systems by putting human needs and their heterogeneity into the spotlight.

RLI

Demand-side mitigation solutions: analyzing the current state of data, opportunities, and paths ahead

Leila Niamir[1], Oreane Edelenbosch[2], Benigna Boza-Kiss[1], Leticia Magalar[3], Shreya Some[4,5], Frauke Wiese[6], Elena Verdolini[7,3], Marlin Arnz[8,20], Huzaifa Butt[9,15], Tao Cao[10], Souran Chatterjee[11], Hsing-Hsuan Chen[2], Yiyi Ju[1], Poornima Kumar[12], Alessio Mastrucci[1], Andreas Mayer[13,14], David McCollum[1,15], Naoko Onishi[16], Joyashree Roy[5,17], Dominik Wiedenhofer[14], Yohie Yamaguchi[18], Carina Zell-Ziegler[19,20], Caroline Zimm[1]

[1] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

[2] Utrecht University, Utrecht, The Netherlands

[3] European Institute on Economics and the Environment (EIEE), Milan, Italy

[4] Technical University of Denmark, Lyngby, Denmark

[5] Asian Institute of Technology, Thailand

[6] Europa-Universität Flensburg, Flensburg, Germany

[7] University of Brescia, Italy

[8] Julich Research Centre, Germany

[9] University of Limerick, Ireland

[10] Univeristy of Tokyo, Japan

[11] University of Plymouth, United Kingdom

[12] University of Oxford, United Kingdom

[13] University of Innsbruck, Austria

[14] BOKU University, Vienna, Austria

[15] Oak Ridge National Laboratory, United States

[16] Research Institute of Innovative Technology for Earth, Japan

[17] Jadavpur University, Kolkata, India

[18] Osaka University, Japan

[19] Oeko-Institut, Berlin, Germany

[20] Technical University of Berlin, Berlin, Germany

Abstract

Demand-side solutions are critical to climate change mitigation as highlighted in the IPCC's Sixth Assessment Report. This research aims to address data gaps to improve the assessment of low-energy demand pathways. Through a systematic literature review, we map the availability of demand-related data across five key sectors: Buildings, Transport, Food, Industry, and Urban sectors. Using the Avoid-Shift-Improve (ASI) framework, we categorize mitigation strategies to identify opportunities for socio-cultural, infrastructural, and technological changes. The study provides insights into existing data availability, highlights current research gaps, and contributes to the development of a more comprehensive understanding of demand-side mitigation potential. Interestingly, the focus of attention varies across the different sectors. The literature review of building sector's role in climate mitigation highlights a strong focus on technological improvements ("Improve" strategies), while "Shift" and especially "Avoid" strategies remain underrepresented despite growing interest. Out of nearly a thousand papers identified, 82% were excluded due to irrelevance, and the remaining studies mostly addressed efficiency improvements such as retrofitting and electrification, with limited focus on sufficiency measures like smaller homes or shared spaces. In contrast food-related mitigation strategies highlights a strong focus on "avoid" (reducing food waste) and "shift" (dietary changes towards plant-based foods), with significantly fewer studies on "improve" (technological innovations like cultured meat). Across all sectors, cost savings alongside GHG reduction remain underexplored, and policy analysis is rare and mostly non-quantitative. Data availability is skewed towards Global North countries, particularly China, Europe, and the U.S., with minimal research on Global South regions. Future research should prioritize a holistic integration of mitigation strategies, expand empirical assessments, incorporate well-being and socio-economic metrics, and enhance policy relevance to translate theoretical mitigation potential into actionable strategies.

Decarbonizing the Building Sector: The Role of Efficiency, Sufficiency, and Behavioural Measures

Authors: Diana Urge-Vorsatz[1], Souran Chatterjee[1,2], Adel Boumerzoug[1]
1. Central European University, Quellenstraße 51, 1100 Wien, Austria
2. University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK

Executive summary

Global energy consumption has increased significantly in 2023, rising by 2.2%, a notable increase compared to the average annual growth rate of 1.5% reported between 2010 and 2019. This increase was largely driven by BRICS nations, which collectively saw a 5.1% increase, accounting for 42% of global energy use. In contrast, energy consumption in OECD countries declined for the second consecutive year, falling by 1.5% due to sluggish economic growth and weak industrial activity. Notable declines were observed in the EU (-4.2%, including a sharp -9.3% in Germany), Japan (-3.5%), and South Korea (-2.8%), while the US maintained stable overall consumption (*World Energy Consumption Statistics | Enerdata*, n.d.). In the US, higher oil use for transportation was offset by reduced electricity demand for cooling and a decline in coal consumption.

The building sector plays a crucial role in reducing energy demand, as it accounted for 30% of global final energy use and 26% of energy-related CO_2 emissions in 2022 (IEA, 2024). Buildings contribute significantly to energy consumption and emissions, with 8% of emissions produced directly by buildings and 18% resulting from electricity and heat generation. While direct emissions from buildings decreased in 2022, extreme weather conditions led to increased heating-related emissions in some regions. At the same time, energy use in the building sector rose by approximately 1%. Many countries are adopting stricter energy codes and performance standards, while energy-efficient and renewable technologies continue to gain momentum. However, the sector must accelerate its transformation to align with the Net Zero Emissions by 2050 (NZE) Scenario.

The next decade is critical to meeting the target of ensuring that all new buildings and 20% of the existing building stock become zero-carbon-ready by 2030. While direct emissions from building operations declined slightly in 2022-after increasing at an

average annual rate of nearly 1% between 2015 and 2021-indirect emissions rose by approximately 1.4% due to increased electricity use. Most IPCC-assessed scenarios project an increase in average floor area per capita. However, many of these studies do not evaluate the effects of sufficiency measures on different end-use demands in the building sector (Gaspard et al., 2023). Consequently, the extent to which energy sufficiency-achieved through floor area reduction and behavioral changes-could lower residential energy consumption remains unclear. As a result, the overall potential of demand-side measures in the building sector is still underestimated.

Therefore, this research explores the potential of behavioral measures in the building sector to facilitate decarbonization under different policy frameworks. It develops two new scenarios-sufficiency and behavioral changes-within the existing High-Efficiency Building (HEB) model to assess the potential impact on countries in both the Global North and Global South.

Findings of this study show that the EU27 region has substantial potential for reducing residential energy demand under both the deep-efficiency and deep-sufficiency scenarios. The deep-efficiency scenario assumes deep energy renovations and high-efficiency construction of new buildings. Based on these assumptions, residential energy demand in the deep-efficiency scenario is projected to decrease by approximately 166% by 2060 compared to 2025. Similarly, under the deep-sufficiency scenario, the reduction potential is estimated at around 167%. This negligible difference suggests that energy efficiency and sufficiency measures achieve almost the same demand reduction potential. A similar trend is observed in North America, where residential energy demand reductions are estimated at approximately 173% and 174% under the deep-efficiency and deep-sufficiency scenarios, respectively. Within the EU, Eastern and Western Europe demonstrate substantial energy demand reduction potential under both the efficiency (173% and 164%, respectively) and sufficiency (174% and 164%, respectively) scenarios by 2060 compared to 2025. Furthermore, it is also highlighted that behavioural changes related to cooling set points and thermal comfort will significantly influence future cooling demand across Africa, China, the Middle East and North Africa (MENA), Latin America, and the USA and other major regions confirms that modest indoor temperature set point increases (by 1 ° C or 2 ° C) can yield substantial energy savings—often 5% to 10% for a +1 ° C shift and 10%–15% for a +2 ° C shift—relative to unchanged settings. For instance, in Africa under a moderate-efficiency pathway, raising the set point from the baseline by 1 ° C lowers 2060 cooling

demand by about 5%, while a 2 ° C adjustment approaches 13% cuts. China exhibits a comparable response (3%–4% for +1 ° C and about 8%-10% for +2 ° C), as does Latin America, where occupant-driven changes alone can reduce demand by roughly 4% (+1 ° C) to 12% (+2 ° C) by mid-century. Similar patterns emerge in MENA (about 5%–13% savings) and the USA (4%-11% savings). These findings highlight that behavioural actions—merely shifting indoor cooling preferences by a few degrees-can be a high-impact, no-cost lever to significantly moderate rising energy use for space cooling in regions poised for rapid growth in cooling demand.

Final Report

Method, Data and Estimation of Cross Sectoral Mitigation Potential of Demand side Solutions with Special Reference to South- and South-East Asia

Submitted by

Asian Institute of Technology, Thailand

PI: Joyashree Roy

Distinguished Professor and Director

Center for South and South-East Asia

Multi-Disciplinary Research Network on Transforming Societies of Global South (SMARTS)

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 V

Project period: June 1, 2024-March 31, 2025

Report period: June 1, 2024-February 28, 2025

Asian Institute of Technology

Contents

1. Participation in workshops/seminars/ conferences 3

1.1 Participation in IIASA's Quarterly workshops/working groups 3

1.2. Workshop/conference panel organised 3

1.3 Presentation in other relevant workshops/seminars/conferences 4

b. Publications:(published with acknowledgement to EDIT) 5

c. Work in Progress 7

- Leading in fast track paper on Cross sector demand side solutions and mitigation potential estimation based on global case studies 7
- Modelling electricity sector demand side flexibility and demand side intervention for countries in South- and South-East Asia. 7
- Bottom-up country specific study for South and South-East Asia on decoupling status. .. 7
- Sufficiency Principle in practice South-east Asian Region 7

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 2024 at Vienna, Austria: Five participants from AIT this year was supported and participated. Joyashree Roy, Joyee Chatterjee, Firuz Ahmed Nahid, Ninaad Prashantbhai Desai, Sirayuth Thongprasert actively participated in person in the Annual EDITS Workshop held in October 7-11, 2024, and actively contributed to the discussion sessions and social events.

c. COP 29

- Joyashree Roy was moderator and speaker at the RITE-IIASA organised EDITS side event session on "Achieving Green Transformation through demand-side changes brought by technology progress and social innovations" at COP 29 to discuss in Japan Pavillion on 13. 11. 2024. https://www.rite.or.jp/system/en/events/2024/12/cop29_1.html. Title of presentation: "Policy as a catalyst in shaping transition for developing countries". (PPT -Annexure 2a)
- Joyashree Roy as chair of Climate Strategies participated at Climate Strategies' Members & Friends Event at COP29: Key research priorities to support climate policy held on 14. 11. 2024. (Annexure1).
- Joyashree Roy Participated in Panel "How spill-over effect help in industrial decarbonization" as a discussant speaker (Annexure 1 and PPT-Annexure 2b) on14.11.2025.

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

Industry (Joyashree, Firuz, Ninaad), Buildings (Firuz, Ninaad), Transport (Ninaad, Joyashree) Data (Sirayuth, Firuz, Joyashree, Ninaad), Narrative (Sirayuth, Joyee) Wellbeing (Sirayuth, Joyee), Protocol (Joyashree, Firuz).

e. Fast track paper activities: Participation from AIT

With LBNL: data, metric and costs and potentials (Joyashree, Huzaifa, Shreya): un
AIT Led: Cross Sector Potential (Joyashree, Ninaad, Firuz)

1.2. Workshop/conference panel organised

"Circular plastic economy: Bridging theory and practice to train future leaders in sustainable plastics research". https://smartscenter.ait.ac.th/post/cpen-project-face-to-face-meeting

1.3 Presentation in other relevant workshops/seminars/conferences

Joyashree Roy

a. was in the panel on "Regional solutions and global lessons: Sustainable cities and communities" at The Global Sustainable Development Congress, Bangkok, 10- 13 June, 2024 (in-person)speaking on demand side solutions for climate change and lifestyle issues.

https://www.timeshighered-events.com/gsd-congress-2024/agenda/session/1298259
https://smartscenter.ait.ac.th/post/global-sustainable-development-congress

b. at UNEP UN Women Dialogue on Actionable Steps for Inclusive Climate Resilience Monitoring and Reporting, July 30, 2024 organized by EmPower and APAN.(annexure 3)

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 4)

d. Srinakharinwirot University, Bangkok at the International Forum on Sufficiency Economy Principle, Climate Crisis and Summit of the Future, September 20, 2024. organised Jointly with UNESCO.

e. Delivered online lecture for

i. University College of London for students in Master in Public Administration (MPA), on Understanding the Multi-dimensional energy-related Challenges in Sustainable Development Context, October 23, 2024.

ii. Hiroshima University, on "Sector-based mitigation: Demands, services and social aspects of mitigation, October 25, 2024

f. Was a speaker at Fireside chat on Bridging the Sustainability Talent Gap: Global South's path forward. At GO ESG 2024 Empowering Talent in achieving the SDGs in Malaysia, Kuala Lumpur. November 7, 2024. https://smartscenter.ait.ac.th/post/fireside-chat-bridging-the-sustainability-talent-gap-asean-s-path-forward-goesg2024

g. Moderated the panel discussion on Panel discussion on : Integrating local policy and action in LCS-RNet , 15th Annual Meeting held virtually organized with IGES on Dec 20, 2024

h. Participated in IPCC AR7 scoping meting in Malaysia Dec 9-13, 2024.

i. Delivered an invited special guest lecture on: Policy and Implementation of Circular Economy at 18th Environment partnership summit & Environment excellence award organized by Indian Chamber of Commerce. Kolkata, India. January 7, 2025. https://smartscenter.ait.ac.th/post/smarts-ait-at-the-18th-icc-environment-partnership-summit-environment-excellence-awards

j. Was an invited discussant in Demand side solutions session in International workshop on "Catalysing energy transition pathways in India for development and sustainability" organized by IIT Delhi, January 20-21, 2025.
k. Presented flash talk on "Why we need to make demand side mitigation solutions a mainstream conversation", presented at the AGM of Climate Strategies, UK , January 29, 2025.
l. Maritime economy in climate change context for Students from Massachusetts Maritime Academy, Boston, USA, Organized by AIT Extension on February 7 (online)
m. Understanding Global Polycrisis to Make Important Choices" organized by RegenIntel Education, February 18th, 2025, (virtual).
n. Climate change Economics, Policies and Actions for students in IIT Guwahati, India on February 19 (online)
o. Energy Neutral Transport for Rivers & Uplands of Sundarban a workshop organized by SAFE, India , February 19.

b. Publications:(published with acknowledgement to EDIT)

1. **Chatterjee, J. S., Thongprasert, S., & Some, S. (2024). Communication, Climate Mitigation, and Behavior Change Interventions: Understanding Message Design and Digital Media Technologies.** ***Annual Review of Environment and Resources*****. https://doi.org/10.1146/annurev-environ-121322-070317**

Abstract
Using the socio-ecological model of social and behavior change communication, our review highlights current trends in understanding message design factors and media technologies promoting pro-environment and climate mitigative behaviors. We explain that much of this research has focused on the individual level, and relatively few studies have been conducted at the inter- personal and community levels. With respect to changing communication ecology, we note the potential for research on the use of social media plat- forms to influence positive behavior changes and, conversely, the challenges of misinformation and its impact on behavior shifts. This area requires further investigation as these communication platforms transform and become increasingly relevant. Additionally, we need to explicate the long-term shifts and impacts of behavior change interventions as well as track behaviors over time. Overall, our review underscores the continued need for research across different geographical, sociopolitical, and technological contexts.

2. **Mohanty Parimita, I. Pal, J. Roy (2024), Improving Community Resilience through distributed solar energy as critical infrastructure- a case study of South Asia, International Journal of Disaster Resilience in the Built Environment, https://doi.org/10.1108/IJDRBE-02-2023-0039.**

Abstract:

Design: Critical infrastructure at community scale needs to be resilient to maintain community-level functionality in the face of adverse impacts. The present study provides two case study sites from Nepal and India, to demonstrate various elements of resilience building for critical infrastructures, especially for the energy sector.

Purpose: The analytical framework proposed in this study links the capital portfolio approach to sustaining human wellbeing, 2015 Sustainable Development Goals (SDGs) and development action ARC-D concepts. Nepal case study is a 'tribrid' power generation system that combines distributed solar, hydro, and wind power generation capacities for the resilience of a community of around 500 people in a remote village with a total installed capacity of 28kW. The second case study is about the solarization of 900 health centres in Chhattisgarh of India, with off-grid solar PV with a cumulative capacity of 3 MW.

Findings:

Granular technology and distributed generation in Nepal and India can act as critical infrastructure in providing on-demand electricity service to enhance community-level resilience along with future opportunities of scale up.

Originality:

The analytical framework for evaluating community-scale resilience through critical infrastructure design and application of the framework using evidence based on case studies are the original contributions.

(Annexure 5)

3. **Creutzig Felix, Joyashree Roy and Jan Minx (2024) Demand-side climate change mitigation: where do we stand and where do we go? Environ. Res. Lett. 19 040201**

DOI 10.1088/1748-9326/ad33d3

(See Annexure 6)

c. Work in Progress

- Leading in fast track paper on Cross sector demand side solutions and mitigation potential estimation based on global case studies
- Modelling electricity sector demand side flexibility and demand side intervention for countries in South- and South-East Asia.
- Bottom-up country specific study for South and South-East Asia on decoupling status.
- Sufficiency Principle in practice South-east Asian Region

Annexure 1

COP 29 report from Joyashree Roy

Activity Report

1. **Active Participation/presentations/talks in three events:**

    a. **As current chair of Climate Strategies: Members meeting of Climate Strategies (photo below) -In Meeting Room 15 (12-1 pm on 14th November)**

Various ongoing projects on Just transition, Coal Transition, Pathways, South-South Cooperation, Governance of new solutions like SRM, CDR etc.. As chair I discussed what might be the future frontier areas of research: e.g., Prospect of Hydrogen economy, Demand side solutions, Just Transitions.

b. Participation in Panel as a discussant speaker (Photo below PPT-attached) in Side-event room 2, on14th at 4.45 -6 PM.

Main take away for me is

How to enable good spillover effects through collaborative trade /industrial policies to achieve industrial sector decarbonization. It is an important research question how on global common issues: be it atmosphere or open ocean, the fragmented world negotiates to progress with new rules for autonomy embedding new collaborative tools in it for a win-win solution with justice. CBAM and various carbon market mechanisms how they can be compared and be included in pathway development to help in policy tool design globally. WTO led multi-institutional report "Working together for Better Climate Action". https://www.wto.org/english/res_e/booksp_e/climate_action_e.pdf

c. EDITS research presentation and Moderation of the EDITS panel in Japan Pavillion (3.45-5PM 15th November) .

i. Main take aways

Question 1: The difference between Early Adopters and Mainstream Adopters? Early Adopters are more environmentally conscious while Mainstream Adopters focus more on rules? Government policy support help overcome issues in the Early Adoption

Question 2: Finance problem of adaptation and mitigation. How do you finance behaviour change?

Question 3: COP pledges are on the supply side, if there were to make demand pledges what would it be?

ii. IPCC AR6 finding showed 40-70 mitigation is possible by 2050 so that can become a content for pledge.
iii. Transport pledge for the demand side already coming up. Demand side pledge for reducing consumption.
iv. Countries have examples of successful reduction consumptions
v. Interaction between demand side and supply side measures to be explored.
vi. The buildings. The more efficient you design your buildings the more cost it will save.

Maybe the need for a new business model. Mobility as a service model, different transport system so that consumer can invest elsewhere.
Better urban planning, urban bus urban improvement, 15-minute city – shorter travel time means the need to invest less in transportation infrastructure. Need to integrate SDGs, not just view finance as separate.
High wellbeing in addition to lower material cost.
First cost is less so easy for the financial institutions and investors to put in money see the opportunity to invest

2. Visited various pavilions to understand the discussions going on in the Side events rooms and in Zone in Delegates Pavilions. Major Take aways from these short visits for me are:
    a. Scientific knowledge building is advancing fast
    b. Community building to ask for more political action building up especially among youths.
    c. Political negotiation is progressing at an incremental pace

Annexure 2a

AIT Asian Institute of Technology

EDITS Energy Demand changes Induced by Technological and Social innovations

RITE Research Institute of Innovative Technology for the Earth

IIASA

Policy as a catalyst

In shaping transition for developing countries

Presented by Joyashree Roy

Please consider the environment before printing this slide deck

Icon from all-free-download.com, Environmental icons 310835, by BSGstudio, license CC-BY

This presentation is licensed under a Creative Commons Attribution 4.0 International License

AIT Asian Institute of Technology

RITE IIASA

Research Questions

How government policy

- plays a catalytic role in deciding technology choice
- strategically manages multidimensional transition

Examples from South Asia and South-East Asia

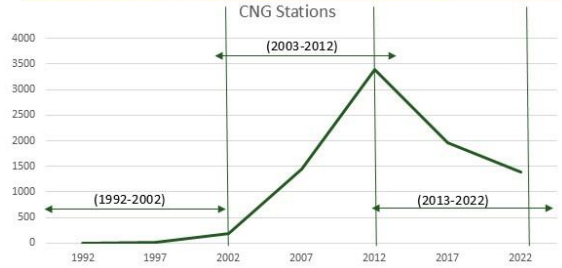
Mobility Sector

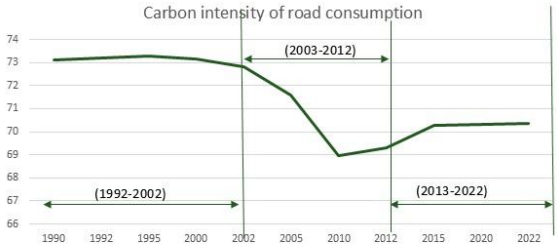
Policy plays a catalytic role in Pakistan for fuel choice in mobility service provision during 1992-2022

- Study funded by RITES under EDITS project and published

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

1992-2022 fuel choice and emission in Pakistan Mobility Sector





Stages of Transition is shorter for developing countries

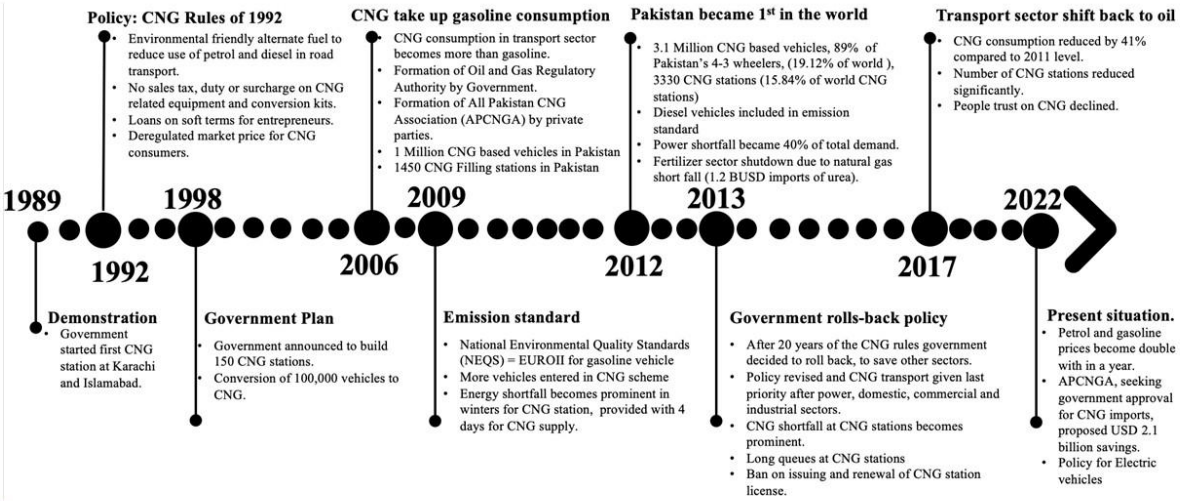
For Developed countries
4 Stages of Transition mentioned in Literature-TIS

For Developing countries
3 Stages of Transition mentioned in our Study-MTIS

- **Emergence** — radical innovation and the learning
- **Early Adoption** — technology purchase, small but steady financial flows the learning process to stabilize the technology innovation
- **Diffusion** — technology is diffused into wider communities and wider market formation.
- **Stabilization/Roll Back**

→ Decision for early adoption 1992-2002
→ Takeoff 2003-2012
→ Roll Back 2013-2022

Policy Driven CNG Transition



Pakistan CNG mobility data and events from last 30 Years 1992 to 2022 and Expert consultation

Decision for early adoption (1992-2002)

Decision for early adoption 1992-2002

Area under Polygon =0.34

1

Take Off (2003-2012)

Take off 2003-2012

Area under Polygon =30.92

2

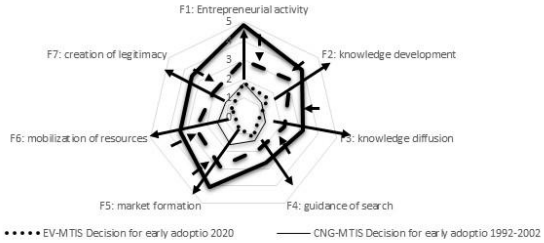
Roll Back (2013-2022)

3

Rollback 2013-2022

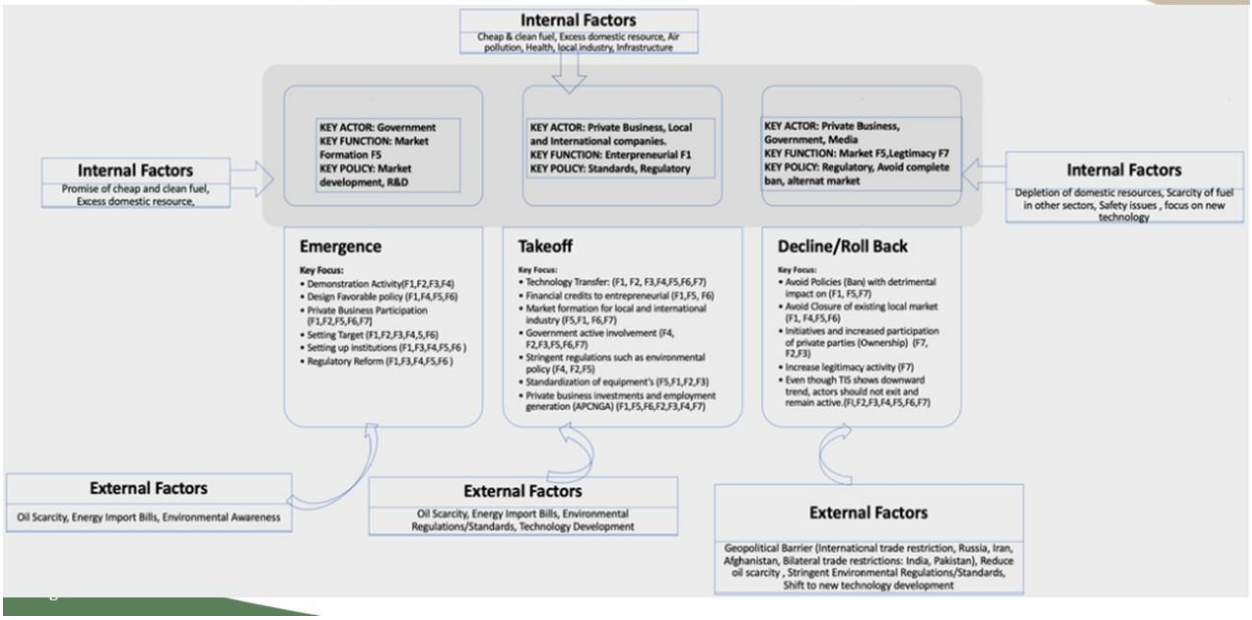
Area under Polygon =1.29

CNG-Existing MTIS(1992-2022) Vs EV- Emerging MTIS(2020-2023)



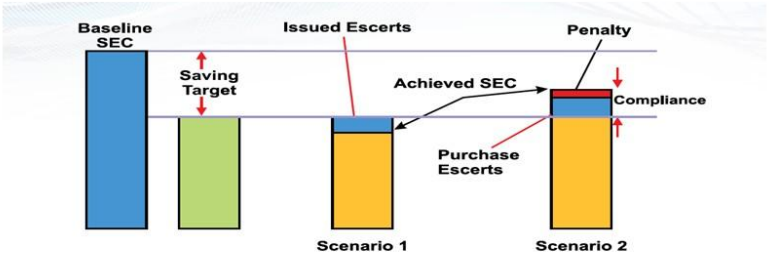
4

successful MTIS for Priority Actions



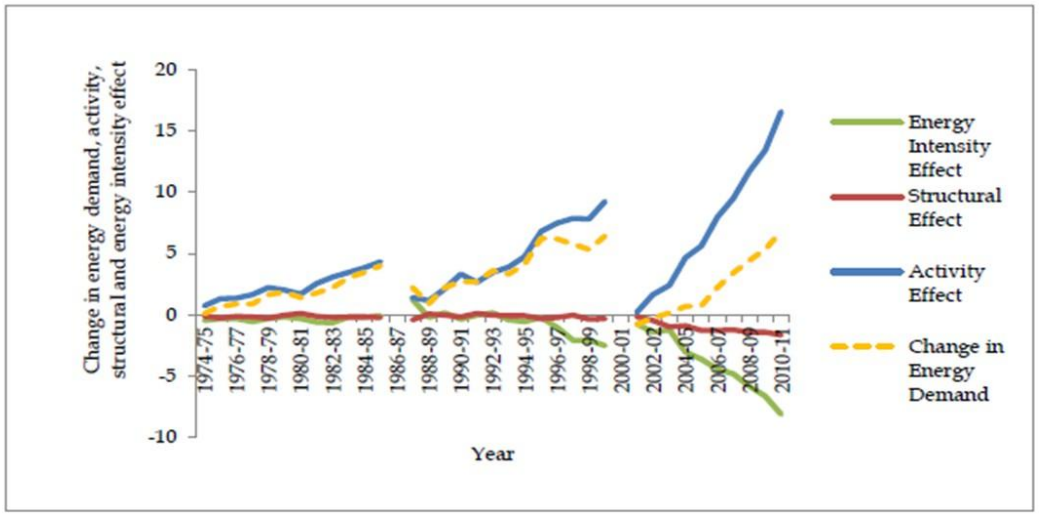
Policy sequence for Indian Industries
Perform Achieve and Trade (under NAPCC 2008)

- Genesis – EC Act, 2001 preceded by multiple policies
- Industries covered – Aluminium, Cement, Chlor Alkali, Fertilizer, Iron and Steel, Pulp and Paper and Textile along with Power sector
- The 478 large energy consuming units -Base line for each unit
- A market based mechanism through certification of energy savings that could be traded



PAT Booklet, Government of India, 2012

Indian Energy Intensive Industry

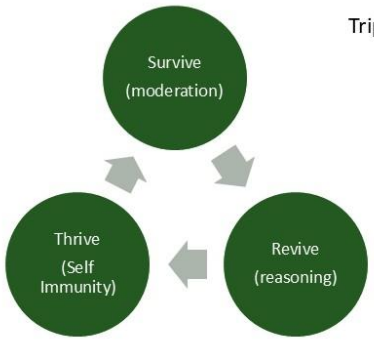


S Dasgupta and J Roy (2016)

Thailand: Sufficiency Economy Principle and Policy ?

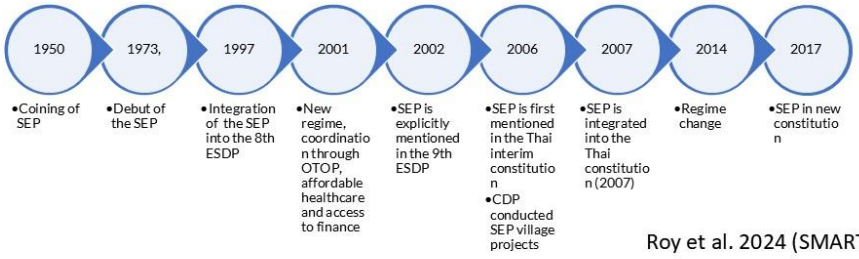
Sufficiency in IPCC 2022-23 report

UNDP (2007) "emphasizing moderation, responsible consumption, and resilience to external shocks"



Tripple Bottom line of SD

Global energy assessment chapter 21 argued that sufficiency in individual consumption can be integrated with efficiency approaches



Roy et al. 2024 (SMARTS/AIT working paper)

EDITS
Energy Demand changes Induced by Technological and Social innovations

Thank you very much for your attention!

Presented by Joyashree Roy
Distinguished Professor and Director (SMARTS Center)
Asian Institute of Technology

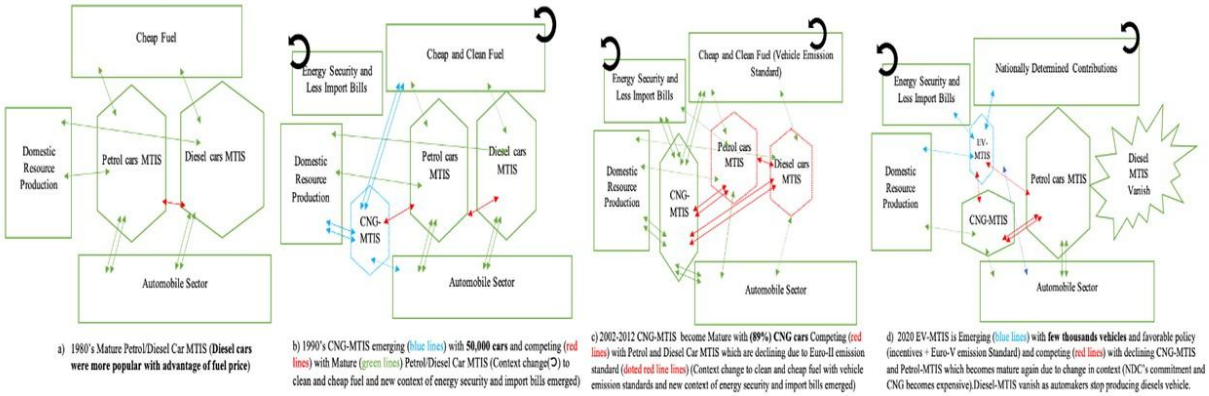
Research support from
Huzaifa Butt, Shreya Some,
Shyamasree Dasgupta, Nandini Das,
SirayuthThongprasert

joyashree@ait.asia
smarts@ait.asia
@Joyashree9
@SMARTS_AIT
https://smartscenter.ait.ac.th/

EDITS is an initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA), and funded by Ministry of Economy, Trade, and Industry (METI), Japan.

This presentation is licensed under a Creative Commons Attribution 4.0 International License

Pakistan Transport Sector Parallel EV-MTIS developments and Competition from external factors



a) 1980's Mature Petrol/Diesel Car MTIS (**Diesel cars were more popular with advantage of fuel price**)

b) 1990's CNG-MTIS emerging (blue lines) with **50,000 cars** and competing (red lines) with Mature (green lines) Petrol/Diesel Car MTIS (Context changeↄ) to clean and cheap fuel and new context of energy security and import bills emerged)

c) 2002-2012 CNG-MTIS become Mature with **(89%) CNG cars** Competing (red lines) with Petrol and Diesel Car MTIS which are declining due to Euro-II emission standard (doted red line lines) (Context change to clean and cheap fuel with vehicle emission standards and new context of energy security and import bills emerged)

d) 2020 EV-MTIS is Emerging (blue lines) with **few thousands vehicles** and favorable policy (incentives + Euro-V emission Standard) and competing (red lines) with declining CNG-MTIS and Petrol-MTIS which becomes mature again due to change in context (NDC's commitment and CNG becomes expensive).Diesel-MTIS vanish as automakers stop producing diesels vehicle.

13

Conclusion [Take home messages]

- CNG-MTIS in Pakistan shows in developing countries policy driven transition management is possible and **policy can be a major enabler.**
- The **decision of early adoption through take-off** phase was a very clear result of **favorable policies and incentive**s matched by efforts from various organizations.
- The **roll-back phase** also demonstrates how policies are being managed to serve the purpose of the regulator or policy maker to **shrink the CNG** based transport system
- This study provides various insights about **role of policy for enabling** such shifts by managing societal acceptance and demand side factors and societal aspects better rather than only focusing on supply side factors to manage a smooth transition.
- CNG-MTIS came with all **positive enabling factors** and new activity, new infrastructure new business opportunities and job were building up and created optimism within the economy which generated social acceptance.
- While **CNG roll back** and **EV decision for early adoption** are happening it is creating surprises to incumbents and losers in very short period of time which can create disruption in the new emergence of new innovation system unless governed carefully by considering the reskilling, retraining and rehabilitation of the prospective losers in the newly emerging system in near term to build a sustainable fast transition towards long term transformation.

14

Annexure 2b

SMARTS
South and South-east Asia
Multidisciplinary Applied Research Network
on Transforming Societies of Global South

Industrial Policy Sequencing:

How Helped Shaping Transition for Indian Industries

Joyashree Roy
Distinguished Professor and Founder Director –SMARTS Center,
Asian Institute of Technology, Thailand.

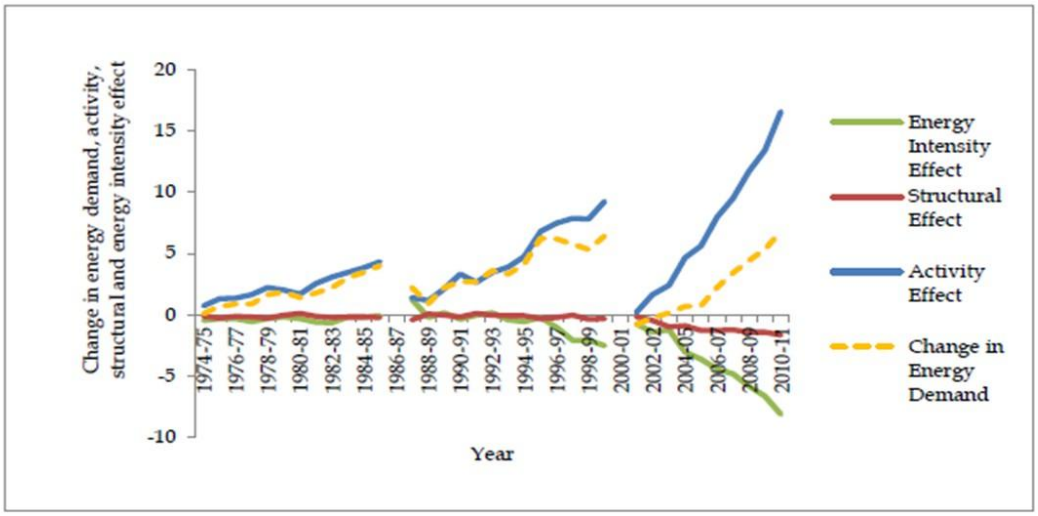
Presented at COP29, Side Event on
Industrial Policy, Trade, and Political Economy of Decarbonization
Co-sponsored by Enel Foundation, Foundation Environment - Law Society, and the Harvard Project on Climate Agreements
Room 2, 2024, Baku.

Policy sequence for Indian Industries

- Genesis – EC Act, 1991, 2001
- Perform Achieve and Trade (under NAPCC 2008)
- Industries covered – Aluminium, Cement, Chlor Alkali, Fertilizer, Iron and Steel, Pulp and Paper and Textile along with Power sector
- The 478 large energy consuming units -Base line for each unit
- A market based mechanism through certification of energy savings that could be traded

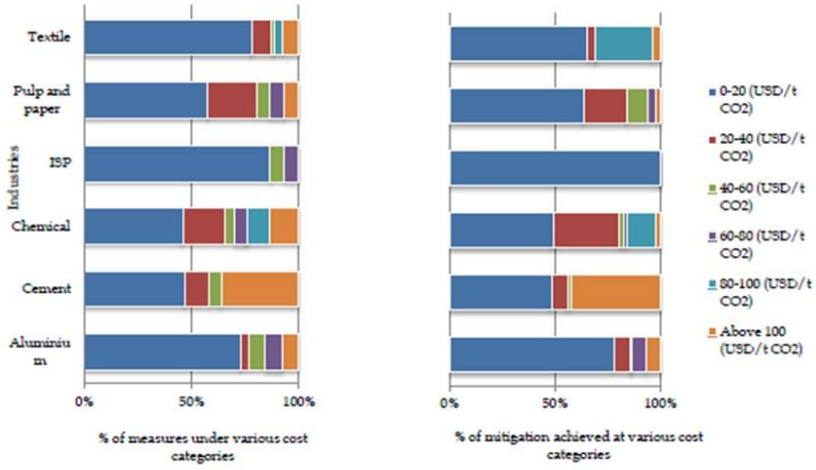
PAT Booklet, Government of India, 2012

Relative decoupling story from India: Industry



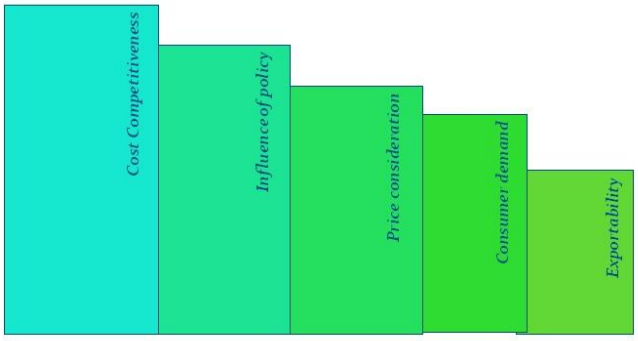
S Dasgupta and J Roy (2016)

Cost borne by the Indian Industries



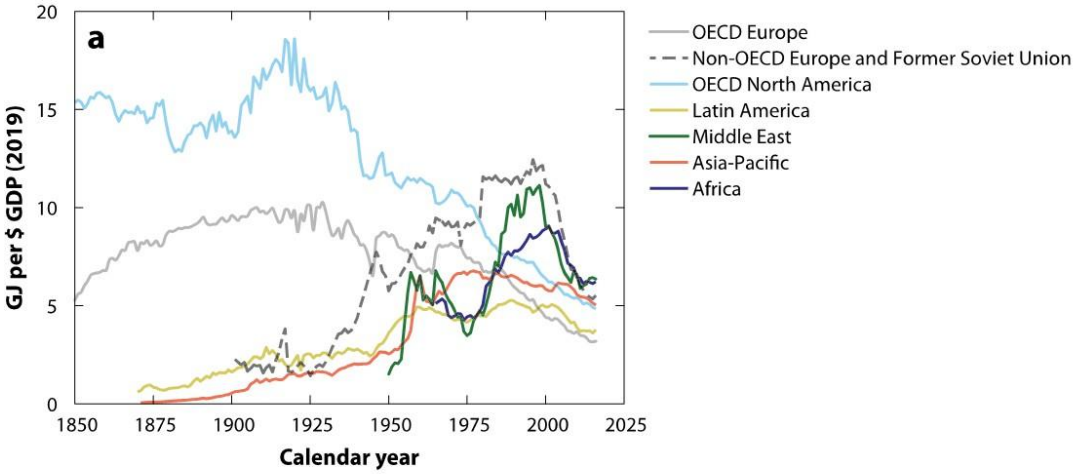
IPCC 2017. ch 10

Why did Industries take the Leadership



Chakraborty and Roy 2013

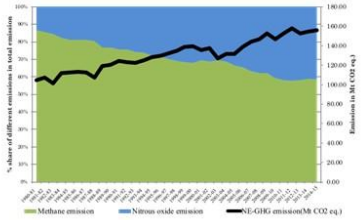
Global Trend was followed by Industries in India



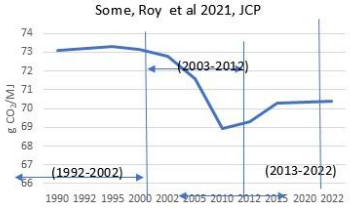
Saunders, Roy et al 2021 ARER

Examples from SA and SEA

Indian Agriculture

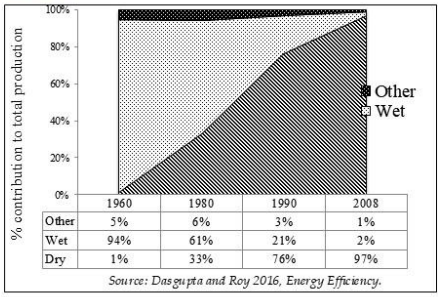


Some, Roy et al 2021, JCP



Pakistan Mobility

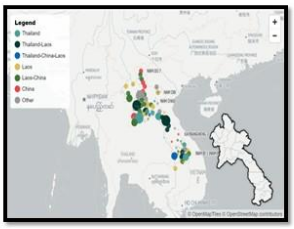
Butt, Roy, Some (ERL 2023)



	1960	1980	1990	2008
Other	5%	6%	3%	1%
Wet	94%	61%	21%	2%
Dry	1%	33%	76%	97%

Source: Dasgupta and Roy 2016, Energy Efficiency.

Indian Industry



Thailand: cross border power trade

3,947MW are hydroelectric power plants, 1,473MW coal-fired power plant

Thank you

joyashreeju@gmail.com
joyashree@ait.asia
https://smartscenter.ait.ac.th/

Annexure 3

Concept Note: Dialogue on Actionable Steps for Inclusive Climate Resilience Monitoring and Reporting

Organized and hosted by the Asia Pacific Adaptation Network (APAN),
and The EmPower: Women for Climate-Resilient Societies Programme

Dates and Registration:
Asia session: 30 July, (Tuesday), 10AM -12 PM, ICT
Pacific session: 1 August, (Thursday), 3-5 PM, WST

Duration: 120 mins including 30 min Q&A
Format: Online on Zoom

Background:

The Asia-Pacific Adaptation Network (APAN) has formed and maintained close partnerships that have established them as a critical adaptation knowledge mobiliser in Asia and the Pacific Region. Similarly, the EmPower: Women for Climate-Resilient Societies Programme (EmPower), jointly implemented by UNEP and UN Women, has demonstrated that joint initiatives can amplify gender responsiveness in the adoption of renewable energy and in the implementation of climate and disaster risk reduction actions. Stakeholders and partners from both initiatives are calling for increased inclusivity and transparency to multistakeholder engagement. APAN and the EmPower programme share the mission of strengthening the participation of Asia Pacific actors to respond to climate change through low carbon development.

This initiative builds on the APAN-SPREP webinar held in June, on "Navigating the Path for the Global Goal on Adaptation" and seeks to enhance implementation of existing adaptation plans. Focusing on inclusivity in monitoring, evaluation, and learning (MEL) systems for climate resilience, the EmPower Programme will host webinars in July and August to engage governments, women organizations, civil society on opportunities to address inclusivity gaps related to the Poverty and Livelihoods, and Food and Agriculture thematic areas of the new UAE Framework for Climate Resilience (Global Goal for Adaptation - GGA) and its UAE-Belem Work Program that were adopted at COP28.

Objectives:

1. To increase knowledge of sub-national, national, and regional actors to design, implement and monitor gender-responsive and inclusive national adaptation plans aligned to the Global Goal on Adaptation targets.
2. To identify potential areas of tailored capacity building support in integrating gender equality and social inclusion in the adaptation policy cycle.

3. Foster a collaborative community amongst governments, women's organizations, civil society, and other key stakeholders, to collectively promote gender equality and inclusion in the new UAE Framework for Climate Resilience (Global Goal for Adaptation - GGA) and its UAE-Belem Work Program.

Expected outputs:

At the end of the session, a summary report will be prepared highlighting the following:

- Summary of knowledge gaps and learning interests from adaptation practitioners, focusing on community and local resilience topics that will inform the design of longer-term capacity building activities.
- Summary of potential entry points for integrating gender equality and inclusion in the development of GGA target indicators through the UAE-Belem work program.

Pacific Session Agenda Date: 1 August 2024, 3-5 PM, WST (Pacific) Moderator: Alexandra Mutungi, (EmPower)		
Time	Activity	Person-in-charge
Opening Session		
1 min	Session opening	Vanessa Carriedo, Coordinator APAN Secretariat
10 min	Setting the context: • Overview of GGA and UAE-Belem Work Program • Integrating cross-cutting themes	Mozaharul Alam, Regional Coordinator, Climate Action, UNEP-ROAP, Head of Office, UNEP India Office (a.i.) and Head, APAN Secretariat
8 min	Welcome remarks	Marlene Nilsson, Deputy Regional Director, UNEP ROAP
5 min	Opening keynote	Prof. Joyashree Roy, Distinguished Professor & Director of SMARTS Center at Asian Institute of Technology,Thailand
2 min	*Interactive session*	Moderator
Session presentation and discussion		
10 min	Introduction to EmPower: Women for Climate Resilient Societies Programme • Overview of EmPower • Vision for Phase II in relation to GGA	Alexandra Mutungi, Gender-Climate Specialist, UNEP
15 min	Gender data driven climate resilience policy cycles (Cambodia Case Study): • Conducting gender-based risk and impact assessments • Designing gender indicators for monitoring, evaluation and learning systems	Rotvatey Sovann, National Programme Officer, UN Women

8 min	Partnerships and awareness raising • Raising awareness and capacity of national climate resilience stakeholders on inclusivity	Prakriti Naswa, Country Engagement Specialist, NDC Partnership
5 min	BREAK	
8 min	Inclusive finance and budgeting for GGA priority areas: • Poverty and livelihoods • Food and Agriculture	Mr. Vatanak Chheng Deputy Head of NCDDS
30 min	Taking stock of implementing crosscutting considerations: • Challenges • Lessons learned • Opportunities for collaboration • Q&A and post session poll	Parimita Mohanty, Programme Management Officer, UNEP (EmPower) & Amy Reggers, Regional Programme Specialist Climate Change and Gender UN Women (EmPower)
Closing session		
5 min	Closing keynote	Mozaharul Alam, Regional Coordinator, Climate Action, UNEP-ROAP, Head of Office, UNEP India Office (a.i.) and Head, APAN Secretariat
Total: 120 min		

Annexure 4

INDIAN ZERO CARBON ENERGY PATHWAYS (IDEEA) Training cum Workshop on OPEN- ENERGY SYSTEM ANALYSIS
(September 2nd and 3rd, 2024 at APJ-103

Day/Time	8.30 AM – 10:45 AM		11.15 AM -1.15 PM		2.30 PM – 4:15 PM		4:45 PM - 5.15 PM
02-09-2024 Monday	**Registration**- 8:30 am to 9:00am; **Inauguration**- 9:30 am to 10:00 am **Keynote**: MF	High Tea	**Modelling Energy Transitions**: JR **Application of SWITCH model for eastern and western region of India**: AM &SC	Lunch	**Hands on IDEEA package**: Lead by Team IISc **The Role of Demand Side Management in Resource Adequacy Planning**: VJ	High Tea	**Use of open source models to inform power sector planning, policy and regulation:** SD
Date/Time	**9:30- 11:30 AM**		**12:00- 1:15 PM**		**2:30- 4:00 PM**		**4:00 – 5 PM**
03-09-2024 Tuesday	**Keynote**: PB **Integration of Virtual Power Plant: A Study in Indian Context:** P **Energy Modelling - Integration of Demand Side Integration:** MN **Modelling Social and Economic Impacts of Renewable Energy Transition :** AD	High Tea	**International Case Studies in modelling of energy transition:** OL		**Research at SHUNYA Lab, DoMS, IITR:** TS **Net Zero Indian electricity system by 2050 or 2070**: AB **Indian electricity system models in SWITCH:** MB **Modeling of Storage in EnergyRt:** AS		**Valedictory Session**: Feedback Distribution of Certificates Vote of Thanks. Followed by Tea

MF	Dr.Matthias Fripp Associate VP EDF	MJ	Manjunath, Young Modeler IISc Bangalore
JR	Prof. Joyshree Roy, Founder SMARTS AIT Bangkok	AD	Abhishek Das Young Modeler IISc Bangalore
AM	Arijit Mukherjee, Jadavpur University	OL	Dr. Oleg Lugovoy Senior Energy Modeller, USA
SC	Sourish Chatterjee, Jadavpur University	TS	Prof. Tarun Sharma DoMS, IIT Roorkee
VJ	Dr. Varun Senior Program manager WRI	AB	Dr. Arvind Singh Bisht, Post Doc IIT Roorkee
SD	Srihari Dukkipati, Fellow Prayas, Hyderabad	AS	Ankit Sharma Young Modeler, IIT Roorkee
PB	Prof. Patil Balachandra, Chief Research Scientist, IISc Bangalore	MB	Mavika Bajpai Young Modeler, IIT Roorkee
P	Praveen Young Modeler IISc Bangalore		

Annexure 5

AIT
Asian Institute of Technology

The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/1759-5908.htm

Case study of South Asia

Improving community resilience through distributed solar energy as critical infrastructure – a case study of South Asia

Parimita Mohanty
United Nations Environment Programme (UNEP), Asia Pacific Office, Bangkok, Thailand

Indrajit Pal
Disaster Preparedness, Mitigation and Management (DPMM), Asian Institute of Technology, Bangkok, Thailand, and

Joyashree Roy
Asian Institute of Technology, Bangkok, Thailand

Received 19 February 2023
Revised 31 January 2024
Accepted 2 April 2024

Abstract

Purpose – The analytical framework proposed in this study aims to link the capital portfolio approach to sustaining human well-being, 2015 sustainable development goals and development action ARC-D concepts. Nepal case study is a "tribrid" power generation system that combines distributed solar, hydro and wind power generation capacities for the resilience of a community of around 500 people in a remote village with a total installed capacity of 28 kW. The second case study is about the solarization of 900 health centres in Chhattisgarh, India, with off-grid solar PV with a cumulative capacity of 3 MW.

Design/methodology/approach – Critical infrastructure at the community scale needs to be resilient to maintain community-level functionality in the face of adverse impacts. The present study provides two case study sites from Nepal and India to demonstrate various elements of resilience building for critical infrastructures, especially for the energy sector.

Findings – Granular technology and distributed generation in Nepal and India can act as critical infrastructure in providing on-demand electricity service to enhance community-level resilience along with future opportunities of scale up.

Joyashree Roy acknowledges funding support under EDIT-AIT project. EDIT-AIT project at the Asian Institute of Technology, Thailand, received funding from the Energy Demand Changes Induced by Technological and Social Innovations (EDITS) project, which is part of the initiative co-ordinated 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]. Indrajit Pal acknowledges funding support under the Coalition of Disaster Resilient Infrastructure (CDRI) fellowship (first cohort 2021–2022) of application number 210117487 and the climate innovation solution "Climate Resilient Infrastructure for Social Transformation and Adaptation (CRISTA)" supported under the Asian Disaster Preparedness Centre (ADPC) Climate Innovation Challenge (CIC), funded by FCDO-UKAID and The World Bank.

International Journal of Disaster Resilience in the Built Environment
© Emerald Publishing Limited
1759-5908
DOI 10.1108/IJDRBE-02-2023-0039

AIT
Asian Institute of Technology

Originality/value – The analytical framework for evaluating community-scale resilience through critical infrastructure design and application of the framework using evidence based on case studies are the original contributions.

Keywords Modern energy, Access to electricity, Enabling investment, Granular technology, Vulnerability and resilience, Distributed electricity generation

Paper type Case study

1. Introduction

In this paper, "community resilience" refers to "uninterrupted access to on-demand electric power supply of a community to enable the community members to maintain individual and collective functionality despite external shocks". Enhancing community resilience through delivery of uninterrupted energy service access ensures multidimensional well-being of the various stakeholders: people and businesses. Infrastructures which enable access to uninterrupted functionality of basic services for a decent living (Rao *et al.*, 2019) to protect the material well-being of members of the community are defined as "critical" in this paper.

One frequent external shock is extreme weather events (Pal and Bhatia, 2017; IPCC, 2018; Roy *et al.*, 2021a, 2021b) and associated power outages due to the direct impact on power infrastructure, primarily through damage of transmission lines or sometimes damage to the small substations in the power supply chain. Power outages interrupt basic functionality in a community through disruption in services like street lighting for the public good, water supply, cooling and heating services, refrigeration service needed both at the household level or in the health centres.

The paper addresses the research question: can community resilience be enhanced through distributed energy supply systems (Lwin *et al.*, 2020; Hasselqvist *et al.*, 2022) which need smaller, modular distribution networks with the opportunity to provide flexibility in innovation, investment, installation and operation, compared to the capital intensive, large technological installations that create long term lock-in impacts?

Over the years, many cities in India, Bangladesh, Cambodia, Thailand (Sothea and Oanh, 2019) and other parts of the region (Peerapong and Limmeechokchai, 2017) households, commercial centres and residential complexes have maintained day-to-day functions by individually owned backup power units which are run mostly by fossil fuels or batteries. However, in recent years, there has been a surge in the deployment of distributed solar mini-grids (Chakravarty and Joyashree Roy, 2021; Mohanty *et al.*, 2019; Sharma *et al.*, 2014) and energy storage systems, which promote uninterrupted power supply to the community's critical facilities such as shelters and household chores, health and medical facilities, communications infrastructure and public safety when the electrical grid system fails. Solar PV-based technology deployment, which has inherent granularity and modularity (Mongabay, 2021), has the potential to enhance the community's resilience with multiple co-benefits such as productivity improvement, carbon emissions reduction potential, local job creation through energy service delivery, local entrepreneurship development of a community to enhance disaster preparedness and emergency operations. There are several interventions already in operation in the Asia Pacific region, such as solar power projects in cyclone shelters of Cox's Bazar, Bangladesh by the World Food Programme (Mehelin, 2020); solar projects installed in public health centres (PHCs) in India and Pakistan, solar portable drinking water system for disaster impacted areas to understand these efforts through a resilience-building lens to help replicate for scale-up (Firstpost, 2021; Aditya Ramji *et al.*, 2017).

This paper consolidates the findings and the best practices from two case studies from India and Nepal, where a distributed solar system is used to provide critical community-scale infrastructure facilities with an uninterrupted power supply to enhance community resilience. Based on learnings from these case studies, the paper discusses what enabling conditions through policy and financing strategies make such interventions successful in resilience building in the face of extreme weather events. The paper focuses exclusively on how distributed solar PVs with battery storage systems protect critical infrastructure, which helps protect the functionalities of basic decent living services in the event of a large-scale power outage as an outcome of a disaster.

2. Analytical framework

Resilience that reflects risk and vulnerability is defined in a variety of ways depending on the context and whose resilience is under consideration. Resilience building for the poor to reduce their vulnerability and exposure to climate-related disasters is a well-established need (Hishan *et al.*, 2021). Social resilience has been at the centre of the discussions in the literature as a way to reduce the magnitude of disaster-related consequences (Marshall and Marshall, 2007; Lwin *et al.*, 2020; Patel *et al.*, 2017; Obrist *et al.*, 2010). A general definition of resilience was published by the National Academies Press, referring to resilience as "the ability to prepare and plan for, absorb, recover from and more successfully adapt to adverse events" (Sharifi, 2016; Sharifi and Yamagata, 2016). The involvement of local communities is fundamental and key to establishing a sustainable and functional early warning system to enhance the capacity for social resilience (Mohanty *et al.*, 2019). The recognition of the continuing vulnerability of communities to a range of multiple hazards needs attention on the capacity building of communities to assess and manage their own risk (Pal *et al.*, 2017).

If people and the attainment of their well-being are at the centre of any solution, then given the current levels of inequality, procedural justice demands faster provision of modern energy sources to all (Roy *et al.*, 2021a, 2021b). This is reflected in the 2015 sustainable development goals (SDGs) (United Nations, 2015). The question is how to meet the dual goal of climate action and modern energy access to enhance the resilience of vulnerable communities. A more fundamental question is how a genuine investment approach (Roy *et al.*, 2021a, 2021b; Roy *et al.*, 2021a, 2021b) can provide a non-declining productive base to ensure the flow of services to the community and the economy and hence build resilience (Roy *et al.*, 2021a, 2021b). It means to build a non-declining productive base, be it for a community, a country or a household and necessitates the maintenance of a capital portfolio, which is also consistent with the sustainable development concept (Hanley *et al.*, 1997).

In this paper, we combine the conceptual framework (Roy *et al.*, 2021a, 2021b), which connects disaster resilience and human well-being, the 2015 SDG framework and the ARC-D framework (analysis of resilience of communities to disaster, ARC-D toolkit, 2016) to provide a structure for evaluating interventions that support community resilience. With this framing of resilience, the authors try to show what components from a system perspective any long-term resilience-building project must have and towards mainstreaming community's development programmes.

The conceptual framework can be operationalised by the community resilience indicators mentioned below in Table 1, which can help examine how distributed renewable energy-based critical infrastructure can contribute to community resilience.

3. Case studies

Two cases from India and Nepal, using the distributed solar system, are presented as means for testing and using the analytical framework to assess long-term community resilience. The information collected through secondary search and from the primary sources through

AIT
Asian Institute of Technology

Community resilience indicators	Questions to be answered	Link to SDGs
Measures to strengthen social and institutional capital		
Community decision-making; inclusion of vulnerable groups; participation of women	Is the community leadership committed, effective and accountable? Are the vulnerable groups in the community included and represented in community decision-making	SDG 1 Indicator 1.1.1 Indicator 1.3.1 SDG 5 Indicator 5.1.1 SDG 10 Indicator 10.4
Access to market	Has the local market grown with energy services and linked for products, labour and services protected against shocks?	SDG 7 Indicator 7.1.2 Indicator 7.2.1
Access to financial services	Whether formal or informal, are there affordable and flexible financial services (savings and credit schemes, microfinance)?	SDG 8 Indicator 8.3.1 Indicator 8.5.1
Social protection; social cohesion and conflict prevention	Does the community have access to informal and formal social protection schemes that support disaster risk reduction and recovery? Is there a sense of peace, security and effective conflict prevention and mitigation mechanisms, both within the community and with other communities?	SDG 1 Indicator 1.1.1 Indicator 1.3.1 SDG 5 Indicator 5.1.1 SDG 10 Indicator 10.4
Leadership and volunteerism in response and recovery	Does the community play a leading role in co-ordinating preparedness, response and recovery, reaching all affected people – including the most vulnerable – through organized and trained volunteers?	SDG 1 Indicator 1.5.1 Indicator 1.5.3 SDG 13 Indicator 13.1.1
Measures to strengthen knowledge capital		
Scientific risk assessment	Does the community combine local knowledge and risk perceptions with scientific knowledge, data and assessment methods?	SDG 1 Indicator 1.5.3 SDG 9 Indicator 9.5.2 SDG 13 Indicator 13.1.1
Education of children on DRR; rights awareness and advocacy	Have community members been exposed to/have participated in DRR specific awareness events (campaigns, discussions and training) and have improved awareness and practices as a result?	SDG 4, Indicator 4.1.1 Indicator 4.3.1 Indicator 4.4.1 SDG 9 Indicator 9.5.2
Measures to strengthen natural capital		
Sustainable environmental management; water security and management	Does the energy infrastructure help the community adopt sustainable environmental management practices that reduce disaster risk and new risks related to climate change? Does the community have access to sufficient water quantity and quality for domestic needs during disasters?	SDG 6 Indicator 6.1.1 Indicator 6.2.1 Indicator 6.4.2 SDG 7 Indicator 7.1.2
Measures to strengthen human capital		
Health access and awareness	Does the energy infrastructure contribute to maintaining the community member's good health in normal times and during a disaster	SDG 3 Indicator 3.8.2 Indicator 3.b.2 Indicator 3.c.1

(*continued*)

Table 1.
Analytical framework to assess community resilience

Community resilience indicators	Questions to be answered	Link to SDGs
Secure and sufficient food supply	Does the energy infrastructure contribute to secure and sufficient food supply during disasters?	SDG 2 Indicator 2.1.1 Indicator 2.1.2 Indicator 2.2.2
Hazard-resistant livelihood practices	Does the community use hazard-resistant livelihood practices for food and income security through this energy infrastructure?	SDG 1, Indicator 1.3.1 Indicator 1.5.2 SDG 8 Indicator 8.8.1 Indicator 8.10.1
Measures to strengthen physical capital		
Household asset protection to maintain income flow	Are household asset bases (income, savings and convertible property) sufficiently large, diverse and protected to ensure reduced vulnerability to disaster?	SDG 11 Indicator 11.5.1 Indicator 11.5.2
Local infrastructure: bridges, hospital, clinic, school building, road and water supply system	Are the community's critical infrastructure and basic services resilient to disaster? Does the community have access to health-care facilities and health workers equipped and trained to respond to disasters' physical and mental health consequences, and is it supported by access to emergency health services and medicines, etc.?	SDG 1 Indicator 1.5.2 Indicator 1.5.3 SDG 9 Indicator 9.a.1 SDG 11 Indicator 11.5.2
Housing	Is the community's housing resilient to disaster?	SDG 1 Indicator 1.3.1 Indicator 1.5.1 SDG 11 Indicator 11. b.1
Early warning system;	Is there an operational early warning system in the community to help with contingency and recovery planning?	SDG 4 Indicator 4.4.1 SDG 9 Indicator 9.b.1 Indicator 9.c.1
Emergency shelter	Are emergency shelters (purpose-built or modified) accessible to the community and have adequate facilities to meet all the affected population's basic needs?	SDG 1 Indicator 1.5.2 Indicator 1.5.3 SDG 9 Indicator 9.a.1 SDG 11 Indicator 11.5.1

Source: Authors

Table 1.

direct interview method and stakeholder consultations is the basic evidence of this study. The following sections describe the case studies in detail.

3.1 Case study-1: Distributed generation: solar wind and micro-hydel system providing critical community-owned infrastructure in Thingan, Makwanpur district, Nepal

Makwanpur district is in the Narayani Zone of the Central Development Region of Nepal, consisting of 43 Village Development Committees (VDCs) and one municipality. The case study is focused on Thingan VDC, one of the VDCs of Makwanpur District with a spatial extent of 27°10' to 27°40'N and 84°41' to 85°31'E (Figure 1).

AIT
Asian Institute of Technology

Figure 1.
Makwanpur district in Nepal

Source: Author

3.1.1 Disasters and challenges faced by communities in Thingan (Makwanpur). As per a research report on "experience sharing on climate change among the local people in Makwanpur district" published by DFID, Action Aid and Women and Children Development Forum, local people belonging to this district are facing an increasing risk from natural hazards such as floods, drought and rise in infectious diseases, which have exacerbated human health and economic impacts. The agriculture sector is the highest impacted economic sector, followed by forestry, biodiversity, water-sanitation, health and hydrology and ecology.

Thingan VDC is experiencing frequent loss of productivity in agriculture, waterborne diseases and lack of access to water at the point of consumption. Thereby the time spent on water collection is high. Geographically disadvantaged terrain with a highly dispersed cluster of households providing electricity access through a conventional national grid expansion system is not cost-effective. As a result, households used kerosene and/or candles for illumination service demand. Few individuals or households with small businesses (as an alternative to their agricultural livelihood) in the main Thingan Bazar rely on kerosene or diesel to run their motive power. The local price of diesel and kerosene was relatively high compared to the market price in central city districts like Kathmandu (almost 30% higher, as per the interaction with the shop owners), and the operational cost of running the business went up, leaving smaller profit margin. Lack of electricity in the main market is considered to be the main hindrance to starting alternate livelihood or expanding existing commercial businesses.

As far as the community-level public infrastructure was concerned, there was no streetlight infrastructure, with narrow village roads and houses on the fringe of the forest. There was a police post, health post, small church library and a co-operative house. Primarily due to lack of electricity: the police post, which is supposed to be open at night, but practically stayed closed, and there was no power source for the wireless mobile, etc. The health post had to close in the evening. In 2009–2010, the police and health posts installed individual solar systems to power the basic equipment to meet the demand for illumination, space cooling and extended work hours at night. However, those smaller solar home systems were insufficient to meet a few critical load requirements, such as powering the vaccine refrigerator and other health-related equipment.

3.1.2 Installation of solar wind micro-hydel hybrid system. In 2011–2012, the solar wind-hybrid system and in 2013, also a micro-hydel system was installed in Thingan VDC. The financial resource of the tribrid renewable energy-based power system came from funds raised by expat Nepalese, Nepal Solar Volunteer Corps (NSVC), a team of university professors and engineering students from various universities in South Korea, with a vision to help and support a remote village in rural Nepal to bring light to those in darkness and uplift the basic living standard of the people there.

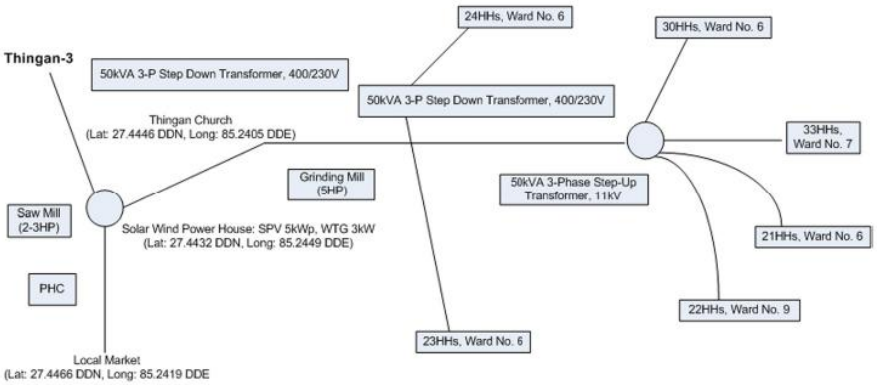
The tribrid system installed at *Thingan VDC of Makwanpur district* consists of:

- 5kW solar PV system;
- 2 kW wind electric generator; and
- 25 kW micro-hydel system.

The 5 kWp solar PV system and wind electric generator were installed in the same location, whereas the micro-hydro site was about 3–4 km from the solar-wind site. The basic sketch below shows the renewable power plants and the loads being provided by those power plants (Figure 2).

A brief description of the tribrid system is given in Table 2.

The five kWp photovoltaic solar system included solar panels, inverters and charge controllers, cables and wiring for transmission lines and homes throughout the village. A small wind turbine with a rated power output of 3.2 kW is installed very close to the location where the solar PV system is installed. The DC electricity generated from the solar PV array and the power generated from the wind are used to charge the battery through the wind-solar charge controller, model: ZY-240 - 8KSW (Figure 3). The battery is then connected to the inverter which converts the DC electricity into single-phase AC electricity distributed within 2 km. Four LED lamps were installed in each home, with each household set to pay a monthly user fee of NRS 150 (US$1.25) flat for up to five units of electricity (kWh) consumption. Hi-tech photo sensor switches were also installed on streetlights to automatically turn them on at dusk and turn them off as the sun shines. The Korean expat Nepalese team technically designed and funded the project, while villagers, with their labour, constructed a building to house the batteries that will store the energy harnessed from solar PV. A User's Committee was also



Source: Author

Figure 2.
Basic schematic of the distribution of power from this tri-hybrid system to different clusters of households

AIT
Asian Institute of Technology

Item	Description	
Total system capacity (in kW)	*28 kW*	
Type of energy generating unit (wind/solar/DG/micro-hydro/others)	*Wind, solar and micro-hydel*	
Available RE resources capacity (in kW)	Solar	*5 kW*
	Wind	*3 kW*
	Micro-hydro	*20 kW*
	Others, if any	*NA*
Daily load profile, if available	*Not available*	
Battery bank	*4800 Ah, 96 V battery bank used in the wind + solar powerhouse*	
Type of distribution network (whether one-phase or three-phase) and length also with voltage rating (11 kV, 400 V, 220 V)	*Transmission lines – three phase, 11 kV* *Distribution lines – one phase, 220 V*	
System voltage level for the solar hybrid system	*220 V*	
Whether the existing systems are grid-tied/off-grid	*Off-grid*	
Metering arrangements (any energy metre used at the household level or another place)	HHs using energy metre – *250* HHs using MCB/cut-out fuse – *250*	

Source: Field visit by lead authors

Table 2.
Brief technical details of the tribrid system

Source: Author

Figure 3.
Solar PV, wind electric generator and battery bank installed at the site

formed at the village level soon after the commissioning of the power system for its regular operation and maintenance of the system. The tariff collected from the end-users is used towards the operation and maintenance of the system.

The new tribrid system has provided electricity to Ward No. 3, 6, 7 and 9 of Thingan VDC, comprising of 250 households. The system gained legitimacy as it got legalized according to the law of the land and is registered in the Chief District Officer's office in Hetauda, Makwanpur, under the name of Miteri Power Plant.

All the components of the MHP plant were in good working condition after one and a half years of installation. About 7 km of transmission lines and more than 10 km of distribution lines have been used. A 24 kW ballast tank is also used to dump any excess power produced (Figure 4).

3.1.3 Scale of the service area for the solar-wind-micro-hydro tribrid system. Almost all the households[1] in these four wards of Thingan VDC, shops in the markets and grinding mills were electrified, which ensured extended hours of productive work and increased income for the shop owners. Every house in the village was provided with Four LED bulbs, each of 7.2 W (made in South Korea and provided by NSVC) and also with a power socket for

Figure 4.
Snapshots of the existing micro-hydropower generating site

Source: Author

charging mobile phones and for using other low power-consuming devices like laptops, TV, radio, fans, etc., the community were able to get latest information regarding various aspects of health, agriculture, entertainment through the mobile.

Health post also started using a refrigerator 24 h per day to make ice to preserve some medicines and vaccines. The library started using computers and LED projectors, as needed, to access the latest information services. The office of the co-operative in the village started using a desktop computer as they are engaged in managing operations and information on the upliftment of the lower-income category people in rural and peri-urban areas through various government schemes. Two tailor shops could use electric iron, and 17 streetlights were installed in Ward No. 3 of the VDC. Local villagers use the rooms attached to the solar and wind powerhouse as poultry farms.

3.1.4 Institutional mechanism and power tariff structure. Institutionally, the User's Committee is responsible for the long-term sustenance of the system and governs other small committees formed in each cluster of houses. These small committees collect tariffs each month and submit them to the main User's Committee. A minimum fixed amount of US$2 per 5 kWh is charged for residential, commercial and community entities (Figure 5).

The situation of the Thingan VDC before and after the installation of the tribrid is summarized in Table 3.

3.2 Case study-2: Solar PV powered rural health centres in rural India

3.2.1 Disasters and challenges faced by communities. In India, the National Rural Health Mission aims to provide the rural population with equitable, affordable and quality health care. Rural India is home to about 889 million (The World Bank, April 2019) primarily dependent on the rural health-care system. India has approximately 29,000 PHCs and 5,500 Community Health Centres. These services are administered via community-owned, decentralized health-care systems, which play an important role in births, immunization, antenatal and neonatal care. The absence of a reliable and quality electric supply system

AIT
Asian Institute of Technology

Figure 5.
Snapshots of shops and health posts using the electricity from the tribrid system

Source: Author

adversely impacts the overall service delivery of the health centres even if the medical equipment and staff are available adequately to prevent and manage any health-related disasters.

This case study considers the solarization of the health centre programme of the Chhattisgarh Renewable Energy Development Agency, a state renewable energy development agency in India, in collaboration with the state health mission. In Chhattisgarh, 900 rural health centres have been installed with off-grid solar PV with a cumulative capacity of 3 MW across the state. The case study has compiled and analysed the improvement of the health-care system by installation of the solar PV system.

3.2.2 Technology and finance. Most of the solar PV systems installed at each PHC site in Chhattisgarh have 2 kW capacity with 48V, 200 Ah battery bank, which can provide a backup of 3–4 h daily to a well-equipped PHC. With the average duration of daily power cut of 2–3 h in most places in the state, these PV systems with battery backup, can provide an uninterrupted, reliable power supply for 24 h to the PHCs.

The original design of the system envisaged the inclusion of illumination and space cooling service through fans in the OPD room, the labour room and the cold chain room and also the connection of the freezer and the ice-lined refrigerator (ILR) to ensure that the cold chain equipment.

As per the field experience, there are PHCs connected to the state power grid with a supply of electricity for more than 85% of the time in a day (locally, they are identified as power non-deficit PHCs). PHCs connected to the state power grid but not with guaranteed continuous supply and thus have unmet power demand (i.e. power deficit PHCs). In total, 26% of the power deficit PHCs have solar PV systems as backup used during power cuts, while around 10% of such PHCs have no solar backup systems.

PHCs that reported severe adverse impact, especially for in-patient and delivery services due to lack of electricity, were significantly higher in number from among the power-deficit PHCs (Figure 6).

Village clusters catered	Before installation	After installation
District	Makwanpur	
Zone	Narayani	
Access to quality electricity supply	None	Residential – 234 HH Commercial – 12 Community entities – police post – 1 Health post – 1 Church – 1 School – 1 Others – street lights – 17 nos. Total: 250
Type of energy services provided	Nil	• *For residential sectors*: four light points and one plug point for charging mobile per household *For community entities*: • A refrigerator in health post for throughout the day • Library used a laptop and an LED projector as needed • Co-operative office in the village used a desktop computer as needed • 17 streetlights have been installed *For commercial entities (shops)*: • Two additional tailor shop • Poultry farm
Addressing climate change by		Clean energy installations through the replacement of fossil fuel-based generating systems.

Source: field survey

Table 3.
Situation of the Thingan VDC before and after the installation of the tri-hybrid system

In total, 27.6% of PHCs with solar power backup (against 8.6% without solar) can keep and successfully run the cold chain equipment, that is, deep freezer and ILR, to provide better health services (Figure 7).

PHCs are the critical infrastructure in the villages. Most of the PHCs with solar power backup confirmed 85%–95% of OPD services, in-patient services and delivery services, which is around 50% higher than the ones with no solar power backup systems. In total, 52% of PHCs reported laboratory services were possible due to solar power systems besides powering lights, fans and cold chain equipment in the laboratory. PHC health services improved by around 50% as the installation of solar systems reduced the impact of power cuts. Some PHCs also reported having reduced incidences of equipment damage due to voltage fluctuation. Demand from PHCs increased at least by 25%–40% more to bear a greater load and thereby reduce their dependence on the grid. About 37% of the sample PHCs reported that their water supply was adversely affected due to a lack of electricity supply, adversely impacting child delivery and the prevention and control of infections. Significant opportunities exist to simultaneously address the (often competing) goals of energy access, energy security, resource management and health outcomes (Table 4). Solar for health is one such example of a success story in Chhattisgarh.

AIT
Asian Institute of Technology

Conclusion

Community resilience building in the provisioning of on-demand electricity service through granular technology and distributed generation is successfully emerging in Nepal and India with scope for scale-up. However, many synergistic actions that need to happen simultaneously to make this systemic change happen and get socially embedded. A case study of Nepal on a distributed generation system innovation using a solar-wind-micro-hydro system in 2013 and a case study of India on widespread solarization provide insights for the scale up of community resilience building through renewable energy. Supply systems in the case study area have addressed the local community level existing unmet demand for modern energy access for productive use.

The case studies help us identify how, following the demand, a successful community scale commercially viable distributed power generation model can be set up to address a basic driver of vulnerability arising out of lack of access to reliable power supply. It is evident from the case study of Nepal that modern electricity is playing an important role in livelihood diversification at the community level. The community also participated in the technology installation and innovation targeted for the community benefit. Technology innovation through the onsite development of the tribrid system in a difficult terrain within a stipulated period created social innovation through trust and human capacity building within the community. However, little exposure of the operator and the community to the technical aspects of the tribrid and its

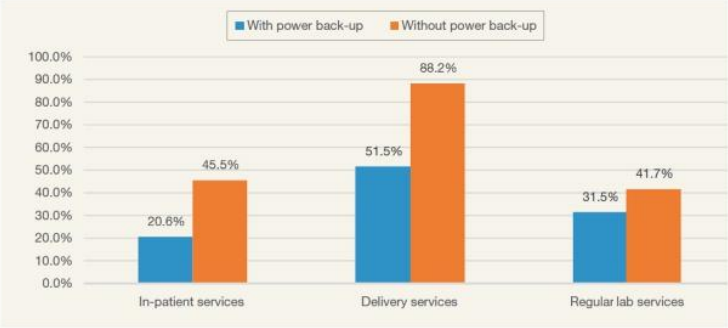


Figure 6.
Comparison of various service levels in PHCs with and without power backup

Source: CEEW Analysis, 2017

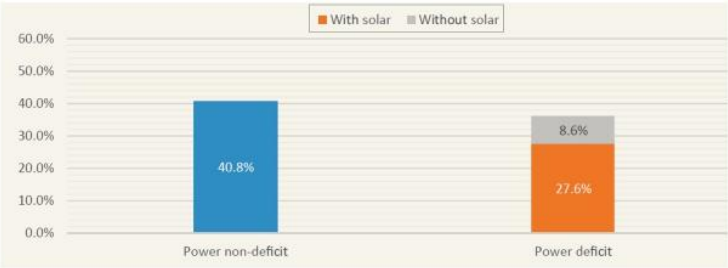


Figure 7.
PHCs with solar power backup

Source: CEEW Analysis, 2017

AIT
Asian Institute of Technology

Table 4.
Community resilience measures and energy access, energy security, resource management and health outcomes

Community resilience measures	Questions	Case study-1	Case study-2
Participatory risk assessment			
Scientific risk assessment	Does the community combine local knowledge and risk perception with scientific knowledge, data and assessment methods?	Yes, the participation of local people with the expatriate scientific team helped in the process and contextualization.	The scope was less as it was more of a ready-to-install technology, but community feedback helped
Education of children on DRR; rights, awareness and advocacy	Have community members been exposed to/have participated in DRR specific awareness events (campaigns, discussions and training) and have improved awareness and practices as a result?	Once the electricity and internet services were available in the village, the community group organized educational and entertainment sessions. Sessions touched upon climate change-related disasters and risks. How far children were involved was not known	Not applicable
Community decision-making; inclusion of vulnerable groups; participation of women	Is the community leadership committed, effective and accountable? Are the vulnerable groups in the community included and represented in community decision-making?	The Village Energy Committee included members from each household, including participation from women. The energy infrastructure brought the community together with a common purpose.	Not applicable as this is not a community-based model
Sustainable environmental management; water security management	Does the community have access to sufficient water quantity and quality for domestic needs during disasters?	Environmental management practices such as using efficient lights, lesser or no use of kerosene or diesel for irrigation purposes, regular cleaning of the stream and availability of water taps for clean drinking water, had been introduced with the hybrid RE system. Drinking water systems linked to the RE system provided water even during heavy rain/drought	Access to regular electricity also enables access to a regular water supply for many PHCs

(*continued*)

AIT
Asian Institute of Technology

Table 4.

Community resilience measures	Questions	Case study-1	Case study-2
Health access and awareness	Does the energy infrastructure contribute to maintaining the community member's good health in normal times and during a disaster?	An uninterrupted power supply to the health clinics from the RE system has substantially increased the possibilities of good health of community members even during a disaster	Services such as cold chain, in-patient care and deliveries were seen to be less impacted due to the lack of grid supply after installing the solar system
Secure and sufficient food supply	Does the energy infrastructure contribute to secure and sufficient food supply during disasters?	Not enough evidence is available. However, the RE infrastructure can also be used to power irrigation systems, cold storage and other food supply systems in the value chain to ensure continuous food supply even during climate shocks and disasters	
Hazard-resistant livelihood practices	Does the community use hazard-resistant livelihood practices for food and income security through this energy infrastructure?	The RE intervention has created a number of livelihood options that were previously unavailable due to a lack of electricity supply	Health officials worked extended hours, which allowed the doctors to serve more outpatients
Access to market	Has the local market grown with energy services and linked products, labour and services protected against shocks?	New businesses came up for extended hours, such as grocery, medicine, cycle repair, flour mills and snack bars	–
Access to financial services	Whether formal or informal, are there affordable and flexible financial services (savings and credit schemes, microfinance)?	Microfinancing institutions had come forward to provide credit schemes for starting new businesses as their confidence level regarding the repayment of the loan increased	Not applicable
Income and asset protection	Are household asset bases (income, savings and convertible property) sufficiently large and diverse and protected to ensure reduced vulnerability to disaster?	No concrete evidence is available.	
	Does the community have access to informal and formal	No concrete evidence is available	

(*continued*)

Community resilience measures	Questions	Case study-1	Case study-2
Social protection; social cohesion and conflict prevention	social protection schemes that support disaster risk reduction and recovery? Is there a sense of peace, security and effective conflict prevention and mitigation mechanisms, both within the community and with other communities?		
Critical infrastructure	Are the community's critical infrastructure and basic services resilient to disaster?		Some of the critical infrastructures, such as health centres, police posts and drinking water facilities, became more resilient due to the supply of reliable electricity and better maintenance of these infrastructures
The solar PV system has made the health infrastructure/PHC more resilient with uninterrupted backup power		Due to the electricity supply from the RE system to the households or PHCs, resilience has increased; however, there is no evidence if the housing is resilient to all kinds of disasters.	
Housing	Is the community's housing resilient to disaster?	–	–
Contingency and recovery planning		–	

(*continued*)

Table 4.

AIT
Asian Institute of Technology

Table 4.

Community resilience measures	Questions	Case study-1	Case study-2
Early warning system	Is there an operational early warning system in the community	No	No
Capacity in preparedness, response and early recovery	–	–	–
Services in emergencies (health, education services)	Does the community have access to health-care facilities and health workers equipped and trained to respond to physical and mental health consequences of disasters supported by access to emergency health services, medicines, etc.?	The community has much better access to the health-care facility and educational facilities due to the reliable supply of power from the RE system, with health workers staying longer hours, access to medicines and vaccines in the health post and PHCs improved	
Emergency infrastructure	Are emergency shelters (purpose-built or modified) accessible to the community and have adequate facilities to meet all the affected population's basic needs?	–	–
Leadership and volunteerism in response and recovery	Does the community play a leading role in co-ordinating preparedness, response and recovery, reaching all affected people – including the most vulnerable – through organized and trained volunteers?	Enhanced community scale activity is a positive trend in this direction	PHCs became institutional support

Source: field survey

associated system (such as safety measures applicable for regions with high altitude and barren land and with the possibility of heavy lightening) may make the infrastructure and services more vulnerable and thus need handholding in the technical and managerial aspect of the tribrid system. State and national governments can play a critical role in rolling out handholding programmes for such interventions to ensure long-term sustainability.

While state-of-the-art technologies can be promoted to achieve better efficiency and reliability of the system, it should plan for the basic and customised training for initial handholding of the local community and dedicated operators. While the Nepal case study explores the enabling factors through the community financing mechanism, the India case study shows enhanced health services through the installation of solar PV systems. However, to scale up such interventions, a better business model can be developed to implement the public-private partnership principle effectively. Public funds can be created and used to identify the appropriate sites and cluster to ensure quality assurance, monitoring and evaluation of the system along with training handholding and awareness campaign; private sector involvement should be in the installation and operation of such system with a fee for service basis or through other revenue model, mutually agreed by all the stakeholders involved.

Recommendations

To build community scale resilience, provision of access to uninterrupted electricity service to community members is a primary necessity. However, without the public sector's active role, only private investment cannot guarantee sustainability. The public sector needs to identify and create a database of sites where distributed generation systems with a diverse mix of local renewable sources need to be set up in the public domain. Public sector investment in awareness building and training of local community members is a primary requisite for private investors to step in with community participation.

Note

1. Few households which are far from the transmission and distribution lines are still not connected and lack access to supply system and are using solar home systems for meeting partially their very minimum basic energy service requirements.

References

Aditya Ramji, A., Sasmita Patnaik, S., Sunil Mani, S., Hem, H. and Dholakia, H.H. (2017), "Powering primary healthcare through solar in India", *Lessons from Chhattisgarh*, CEEW Report and Oxfam India.

Chakravarty, D. and Joyashree Roy, J. (2021), "Solar microgrids in rural India: a case study of household benefits", *Ecology, Economy and Society–the INSEE Journal*, Vol. 4 No. 2, pp. 65-93, available at: https://ecoinsee.org/journal/ojs/index.php/ees/article/view/140

Firstpost (2021), available at: www.firstpost.com/world/at-sindhs-primary-healthcare-centres-solar-power-is-helping-save-the-lives-of-mothers-9396071.html

Hanley, N., Shogren, J.F. and White, B. (1997), *Environmental Economics in Theory and Practice*, Macmillan, Bristol.

Hasselqvist, H., Renström, S., Strömberg, H. and Håkansson, M. (2022), "Household energy resilience: shifting perspectives to reveal opportunities for renewable energy futures in affluent contexts", *Energy Research and Social Science*, Vol. 88, doi: 10.1016/j.erss.2022.102498.

Hishan, S.S., Ramakrishnan, S., Mansor, N.N.B., Rahim, A.R., Chuan, L.T., Mahmood, A. and Beri, N. (2021), "Understanding disaster risk and development of resilience as one of the fundamental

drivers of sustainable development in India with special reference to super cyclone Amphan", *International Journal of Disaster Risk Reduction*, Vol. 62, doi: 10.1016/j.ijdrr.2021.102339.

IPCC (2018), "Summary for policymakers. In: global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty", in Masson-Delmotte, V.P., Zhai, H.-O., Pörtner, D., Roberts, J., Skea, P.R., Shukla, A., Pirani, W., Moufouma-Okia, C., Péan, R., Pidcock, S., Connors, J.B.R., Matthews, Y., Chen, X., Zhou, M.I., Gomis, E., Lonnoy, T., Maycock, M., Tignor. and Waterfield, T. (Eds), *World Meteorological Organization*, Geneva, Switzerland, p. 32.

Lwin, K.K., Pal, I., Shrestha, S. and Warnitchai, P. (2020), "Assessing social resilience for flood-vulnerable communities in Ayeyarwady Delta, Myanmar", *International Journal of Disaster Risk Reduction*, Vol. 51, p. 101745, doi: 10.1016/j.ijdrr.2020.101745.

Marshall, N.A. and Marshall, P.A. (2007), "Conceptualizing and operationalizing social resilience within commercial fisheries in Northern Australia", *Ecology and Society*, Vol. 12 No. 1, doi: 10.5751/ES-01940-120101.

Mehelin, N. (2020), *Cox's Bazar: 40 Cyclone Shelters Offer Protection for 40,000 People*, WorldFood Program, Bangladesh.

Mohanty, A., Hussain, M., Mishra, M., Kattel, D.B. and Pal, I. (2019), "Exploring community resilience and early warning solution for flash floods, debris flow and landslides in conflict prone villages of Badakhshan", *International Journal of Disaster Risk Reduction*, Vol. 33.

Mongabay (2021), "Rooftop solar prepares prosumers in Odisha for power cuts during disasters", available at: https://india.mongabay.com/2021/11/solar-energy-prepares-prosumers-in-odisha-for-power-cuts-during-disasters/ (last updated in Nov 2021).

Obrist, B., Pfeiffer, C. and Henley, R. (2010), "Multi-layered social resilience: a new approach in mitigation research", *Progress in Development Studies*, Vol. 10 No. 4, pp. 2010-2293, doi: 10.1177/146499340901000402.

Pal, I. and Bhatia, S. (2017), "Disaster risk governance and city resilience in Asia-pacific region", *Science and Technology in Disaster Risk Reduction in Asia: Potentials and Challenges*, pp. 137-159, doi: 10.1016/B978-0-12-812711-7.00009-2.

Pal, I., Ghosh, T. and Ghosh, C. (2017), "Institutional framework and administrative systems for effective disaster risk governance – perspectives of 2013 cyclone phailin in India", *International Journal of Disaster Risk Reduction*, Vol. 21

Patel, S., Rogers, M., Amlˆot, R. and Rubin, G. (2017), "What do we mean by 'community resilience'? A systematic literature review of how it is defined in the literature", *PloS Curr. Disasters*, Vol. 9.

Peerapong, P. and Limmeechokchai, B. (2017), "Optimal electricity development by increasing solar resources in diesel-based micro grid of island society in Thailand", *Energy Reports*, Vol. 3, pp. 1-13, doi: 10.1016/j.egyr.2016.11.001.

Rao, N.D., Min, J. and Mastrucci, A. (2019), "Energy requirements for decent living in India, Brazil and South Africa", *Nature Energy*, Vol. 4 No. 12, pp. 1025-1032, doi: 10.1038/s41560-019-0497-9.

Roy, J., Islam, S.T., Pal, I. and Mahmud, H. (2021a), "A white paper on: top ten priorities: in implementation of low carbon sustainable energy development and adaption framework to reduce disaster impact in the context of Bangladesh, Bangabandhu chair special issue, energy, disaster, climate change: sustainability and just transitions in Bangladesh", *International Energy Journal*, Vol. 21 No. 1A, pp. 143-145.

Roy, J., Islam, S.T. and Pal, I. (2021b), "Implementation framework for sustainable development: what matters in the context of Bangladesh, bangabandhu chair special issue, energy, disaster, climate change: Sustainability and just transitions in Bangladesh", *International Energy Journal*, Vol. 21, pp. 1-8.

Sharifi, A. (2016), "A critical review of selected tools for assessing community resilience", *Ecological Indicators*, Vol. 69, doi: 10.1016/j.ecolind.2016.05.023.

Sharifi, A. and Yamagata, Y. (2016), "On the suitability of assessment tools for guiding communities towards disaster resilience", *International Journal of Disaster Risk Reduction*, Vol. 18 No. 2016, doi: 10.1016/j.ijdrr.2016.06.006.

Sharma, K.R., Palit, D., Mohanty, P. and Gujar, M. (2014), "Approach for designing solar photovoltaic-based mini-grid projects: a case study from India", in Bhattacharyya, S. and Palit, D. (Eds), *Mini-Grids for Rural Electrification of Developing Countries. Green Energy and Technology*, Springer, pp. 167-201, doi: 10.1007/978-3-319-04816-1_8.

Sothea, K. and Oanh, N.T. (2019), "Characterization of emissions from diesel backup generators in Cambodia", *Atmospheric Pollution Research*, Vol. 10 No. 2, pp. 345-354, doi: 10.1016/j.apr.2018.09.001.

United Nations (2015), "Transforming our world: the 2030 agenda for sustainable development", available at: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf

Further reading

Clark-Ginsberg, A.B., McCaul, B., Bremaud, I., Cáceres, G., Mpanje, D., Patel, S. and Patel, R. (2020), "Practitioner approaches to measuring community resilience: the analysis of the resilience of communities to disasters toolkit", *International Journal of Disaster Risk Reduction*, Vol. 50, doi: 10.1016/j.ijdrr.2020.101714.

Gibson, M.J., Chen, A.S., Khoury, M., Vamvakeridou-Lyroudia, L.S., Stewart, D., Wood, M. and Djordjević, S. (2020), "Case study of the cascading effects on critical infrastructure in torbay coastal/pluvial flooding with climate change and 3D visualisation", *Journal of Hydroinformatics*, Vol. 22 No. 1, pp. 77-92.

Gujar, M., Datta, A. and Mohanty, P. (2013), "Smart mini grid: an innovative distributed generation based energy system", 2013 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia), pp. 1-5, doi: 10.1109/ISGT-Asia.2013.6698768.

Medium.com (2024), available at: https://medium.com/world-food-programme-insight/combatting-natural-disasters-with-cyclone-shelters-d711e27d2fa8

Rao, N.D. and Min, J. (2017), "Decent living standards: Material prerequisites for human wellbeing", *Social Indicators Research*, Vol. 138 No. 1, pp. 225-244, doi: 10.1007/S11205-017-1650-0.

Thanvisitthpon, N., Shrestha, S. and Pal, I. (2018), "Urban flooding and climate change: a case study of bangkok", *Environment and Urbanization ASIA*, Vol. 9 No. 1.

Thanvisitthpon, N., Shrestha, S., Pal, I., Ninsawat, S. and Chaowiwat, W. (2020), "Assessment of flood adaptive capacity of urban areas in Thailand", *Environmental Impact Assessment Review*, Vol. 81.

Corresponding author
Indrajit Pal can be contacted at: indrajit-pal@ait.ac.th

For instructions on how to order reprints of this article, please visit our website:
www.emeraldgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: **permissions@emeraldinsight.com**

Annexure 6

ENVIRONMENTAL RESEARCH
LETTERS

EDITORIAL • OPEN ACCESS

Demand-side climate change mitigation: where do we stand and where do we go?

To cite this article: Felix Creutzig *et al* 2024 *Environ. Res. Lett.* **19** 040201

View the article online for updates and enhancements.

You may also like

- Climate change mitigation in cities: a systematic scoping of case studies
Mahendra Sethi, William Lamb, Jan Minx et al.
- Reviewing the scope and thematic focus of 100 000 publications on energy consumption, services and social aspects of climate change: a big data approach to demand-side mitigation
Felix Creutzig, Max Callaghan, Anjali Ramakrishnan et al.
- Coal transitions—part 1: a systematic map and review of case study learnings from regional, national, and local coal phase-out experiences
Francesca Diluiso, Paula Walk, Niccolò Manych et al.

This content was downloaded from IP address 203.159.58.113 on 27/03/2024 at 07:06

AIT
Asian Institute of Technology

IOP Publishing Environ. Res. Lett. 19 (2024) 040201 https://doi.org/10.1088/1748-9326/ad33d3

ENVIRONMENTAL RESEARCH
LETTERS

EDITORIAL

Demand-side climate change mitigation: where do we stand and where do we go?

Felix Creutzig[1,2,*], Joyashree Roy[3] and Jan Minx[1,4]

[1] Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany
[2] Sustainability Economics of Human Settlements, Technische Universität Berlin, Berlin, Germany
[3] Asian Institute of Technology, Bangkok, Thailand
[4] Priestley Centre for Climate Futures, School of Earth and Environment, University of Leeds, Leeds, United Kingdom
[*] Author to whom any correspondence should be addressed.

E-mail: creutzig@mcc-berlin.net

OPEN ACCESS

RECEIVED
22 February 2024

ACCEPTED FOR PUBLICATION
14 March 2024

PUBLISHED
22 March 2024

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Abstract

It is now well established that the demand side can contribute substantially to climate change mitigation thus increasing the solution space. The recent IPCC synthesis report for the first time explicitly reflected this class of solutions. Here, we provide an overview of an unique set of 22 review papers published in the focus issue of Environmental Research Letters. We also extract a key set of insights, ranging from the varied but rapidly evolving literature to demand-side mitigation potential, relevance for well-being, and consistent categorization of options across end-use sectors. We find that demand-side approaches to climate change mitigation supplement exclusively technology-focused supply side solutions and, in many cases, comprise system-wide effect contributing to well-being and planetary stability. Review studies cover macro-economics, well-being, and sustainable development goals on the metric side, and investigate consumption-based individual options, urban strategies, transport, building, and food sector potentials, but also the role of the circular economy, material efficiency, and digitalization. Demand-side measures can be categorized into avoid, shift, and improve approaches. Several additional reviews systematically investigate psychological and social approaches and initiatives to foster climate change mitigation. We finally outline important gaps and questions to be tackled in the coming years.

In this editorial, we synthesize a special issue and the findings from 22 systematic reviews on climate change mitigation that identify and scrutinize demand-side solutions for climate change mitigation. These reviews provide a comprehensive overview of the current state of research in this vital area, helping to shape and substantiate the most recent IPCC report (Skea *et al* 2022, Creutzig *et al* 2022b). Demand-side climate change mitigation is increasingly recognized as essential for achieving ambitious climate targets, supplementing supply side solutions firmly embedded in climate stabilization scenarios. This collection of reviews is particularly timely, given the pressing need to address these targets, but also considering the potential benefits of demand-side solutions for society. These solutions not only help in reducing greenhouse gas (GHG) emissions but also offer services that increase well-being and are consistent with broader planetary stability goals, such as reduced land use.

The demand-side of climate change has always been implicit in economic and social science research on climate change mitigation, but until recently has not been explicitly covered and quantified in assessment on climate solutions. A review synthesized how the 5th IPCC assessment report provided cases and examples on demand-side climate change mitigation in various chapters (Creutzig *et al* 2016). In a community wide effort, an outline of the scope of demand-side climate change mitigation was explored, highlighting the categorization of demand-side measures into avoid, shift, and improve (ASI) approaches (Creutzig *et al* 2018). We will see that this simple ASI categorization recurrently appears in this focus issue.

In this editorial, we discuss the review papers in 5 clusters. First, we start with an overview of

© 2024 The Author(s). Published by IOP Publishing Ltd

AIT
Asian Institute of Technology

the literature base. It begins with a discussion on 'History and Narratives', providing context and background on the evolution of demand-side mitigation. This is followed by an exploration of the 'Political Economy', assessing the influence of various stakeholders and economic factors. The next section, 'Economics of Transitioning', delves into the financial and economic implications of adopting demand-side strategies. Additionally, the 'Geography' section aims to address regional disparities and the unique challenges faced by different areas in implementing these strategies. Through these clusters, the editorial aims to provide a comprehensive understanding of demand-side climate change mitigation, setting the stage for the detailed reviews that follow.

1. The literature on demand-side solution evolves rapidly, and even more so than the climate change solution literature in general

A thorough analysis of the literature of demand side of climate change mitigation first requires a map of the literature and an accompanying definition of which part of the literature does so. The review titled 'Reviewing the scope and thematic focus of 100 000 publications on energy consumption, services and social aspects of climate change: a big data approach to demand-side mitigation' (Creutzig *et al* 2021) does so and presents a comprehensive review of literature on energy consumption, services, and social aspects of climate change. The review is based on a big literature data approach and focuses on demand-side mitigation.

The authors used a two-pronged approach to gather data. First, they used a top-down search query that yielded around 30 000 results. They then asked domain experts to identify five of the most important papers in their specific field relevant to demand, services, and social aspects of mitigation. Interestingly, over 50% of these papers were not discovered by the top-down query.

To address this, the authors developed 27 search queries that investigated aspects of the issue list in much more detail. These queries found 63 847 documents, of which 34% (21 913 documents) were also identified by the top–down search query. This means that expert queries identified two-thirds of documents not yet obtained by the top-down query, highlighting the important role of domain-experts in deriving search queries. The overall growth of the literature outperforms the overall literature on climate change solutions.

The authors then used topic modeling, an unsupervised machine learning technique, to explore the content of the studies in their queries, identifying four key clusters: policy, housing, mobility, and food/consumption. The mobility literature, specifically, sheds light on the significant role of transport in climate change mitigation, emphasizing the need for shifts in transport modalities and improved urban infrastructure to reduce dependency on personal vehicles. This insight is crucial in understanding how changes in mobility patterns can significantly contribute to reducing GHG emissions and enhancing urban sustainability. The housing literature emphasizes investments and refurbishment by homeowners, but also social and collective action, while the food/consumption literature points to the importance of behavioral change and its dynamic interaction with social norms. These clusters suggest that demand-side solutions can significantly improve public health. The centrality of the policy cluster within these findings underscores the critical role of political actions in integrating and enhancing the effectiveness of various demand-side approaches. This comprehensive analysis maps the underlying epistemic communities, demonstrating the interconnectedness of these areas of study in the broader context of demand-side climate change mitigation.

The study concludes that while the generic search of the 'chapter' queries is good at identifying the overall topics, expert domain queries find a high amount of additional literature (41 934 documents), making expert search queries and knowledge important for identifying in-depth literature.

A complementary, 'Systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping' (Wiedenhofer *et al* 2020) investigates the literature on how macro-economic metrics relate to climate change mitigation. The systematic map and review scrutinizes the empirical literature on decoupling, focusing on the observed relationships between economic growth (approximated as GDP growth), resource use decoupling (materials, energy), and impact decoupling for GHG emissions on the national to global scale. The authors aim to understand the development of the relevant research streams, their conceptual and methodological approaches, and limitation, identifying three focal areas: energy flows and energy conversion chains in socio-economic systems, a more comprehensive perspective asserting that materials and energy are necessarily interlinked, and a stream based on data obtained from material and energy flow analysis. The authors find that decomposition and regression analyses (28%) and econometric time-series analyses (24%) are the most prevalent methods used in the studies. They also find that 46% of the analyses are single-country analyses, with China leading with 157 analyses, followed by the USA with 31 analyses.

AIT
Asian Institute of Technology

The results implicate that future work should focus on comprehensive multi-indicator long-term analyses, conceptually grounded on the fundamental biophysical basis of socio-economic activities, incorporating the role of global supply chains as well as the wider societal role and preconditions of economic growth. The authors also suggest that understanding the interdependencies between economic growth and resource use and/or emissions is crucial, an area where demand-side measures play an important role.

2. Demand-side mitigation is an essential and relevant strategy to achieve climate goals especially in the mid-term until 2050

What is the overall scope and potential of demand-side solutions for climate change mitigations? In a review study in Nature Climate Change, aligning and quantitatively synthesizing the findings of this focus issue, Felix Creutzig *et al* comprehensively assess demand-side mitigation strategies for climate change and their impacts on well-being (2022a). The study categorizes these strategies into ASI options across various end-use sectors and identifies their aggregate mitigation potentials. The findings indicate that demand-side options can reduce sectoral emissions by 40%–70% until 2050, with largely beneficial effects on well-being: 79% of these impacts are positive, 18% neutral, and only 3% negative, emphasizing that such strategies not only aid in climate mitigation but also enhance various aspects of human well-being.

A systematic review of macro-economic factors, such as GDP, and their effect on GHG emissions substantiates the relevance of demand-side measures for achieving the goals of the Paris agreement. Specifically, 'A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights' provides a comprehensive review of the relationship between economic growth and various resource-use and emission indicators (Haberl *et al* 2020).

The authors conducted a qualitative synthesis of strategies and policy recommendations by drawing a random subsample of 15% from 835 articles, yielding 125 articles for further qualitative content synthesis. They used definitions of green growth and degrowth to interpretatively map the 125 papers. Articles were classified as 'green growth' if their framing aimed at absolute or relative decoupling without impeding economic growth. Articles were classified as 'degrowth' if their framing explicitly challenged the primacy of economic growth over the (absolute) reduction of resource use and emissions. Papers not meeting these criteria were classified as 'others'.

The review reveals that most observed decoupling is relative (less GHG emissions per unit of GDP) but not absolute (reduced GHG emissions). However, several countries display absolute decoupling, including a reduction in consumption based emissions (Quéré *et al* 2019, Lamb *et al* 2021). While there can be optimism on accelerating decarbonization in the energy sector due to low cost renewables (Creutzig *et al* 2023), Haberl *et al* rightly emphasize that demand-side measures, focused on improving well-being, while keeping energy use and GHG emissions low, are key to maintain the feasibility of keeping temperatures below 2 °C. Another review in this focus issue (see also below) proposes that the development of well-being approaches of mitigation pathways should be a new research direction (Saujot *et al* 2020). They suggest that the concept of lifestyle is a pivotal notion for such research, which will contribute to improving the assessment of pathways in terms of desirability, and thus feasibility.

In this light, Haberl *et al* also argue that GDP may be becoming an increasingly irrelevant measure of welfare, as it was only loosely coupled with well-being in OECD countries over the last 40 years. They suggest that GDP should be replaced or at least complemented by measures of wellbeing and planetary health. The question of how a good life for all on the planet can be organized within the planet's environmental limits may be more important than the extent to which GDP can be decoupled from resource use or emissions.

Demand-side measures are not only effective but also align well with sustainable development goals (SDGs) and the corresponding well-being dimensions, a key insights of the review 'Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search' (Roy *et al* 2021) (see also (Creutzig *et al* 2022a) for a comprehensive well-being assessment). Similar to Ivanova *et al*, Roy *et al* categorize various demand side actions into the ASI categories. The 'Avoid' category includes actions aimed at avoiding the demand for high-emission intensive services; actions in the 'Shift' category help in substituting demand for high-emission intensive services with low/no intensive ones; and 'Improve' category actions are aimed at improving the energy/emission intensity of a service type.

The review finds that most of these demand side mitigation actions showed positive linkages with SDGs 7 (Affordable and Clean Energy), 9 (Industry, Innovation, and Infrastructure), and 11 (Sustainable Cities and Communities), highlighting the importance of looking at the longer term in a sustainability context, such as the performance of green buildings and the rebound effect of energy efficiency. Demand side actions to be effective enough need a systemwide embedding. For optimizing the mitigation actions, the interconnectedness across sectors is important. For example, demand side mitigation actions in the transport sector are highly dependent

⑪-1.AIT

AIT
Asian Institute of Technology

on city planning and infrastructure, as also emphasized in novel technical estimates (Nachtigall *et al* 2023), and the construction sector is an integral part of the building sector.

For the relevance of demand-side measures, Roy *et al* suggest that a better understanding of the costs and benefits of these solutions could facilitate higher adoption. High upfront costs of low carbon options, inadequate infrastructure, incorrect understanding or low awareness regarding sustainable options, and socio-cultural factors currently limit uptake.

However, there are also trade-offs, for example at the interface between adaptation and energy demand. The study 'When adaptation increases energy demand: a systematic map of the literature' provides a comprehensive review of the literature on the impact of adaptation measures on energy demand (Viguié *et al* 2021), also investigating adaptation actions that moderate energy demand.

The number and type of actions studied are very heterogeneous across the studies. Among the many adaptation alternatives considered, 'better insulation' and 'use of shading devices/blinds' stand out as most frequently cited. Both appear and are quantified in about a third of the papers. Approximately 65% of the papers have a geographical resolution smaller than a country (e.g. states, provinces, or cities), and only a quarter (26%) rely on data at the country scale. Only four articles quantify alternatives at the regional or global scale.

The review finds that the choice of adaptation pathways studied in the papers strongly depends on the scale of the studies and the methodology used. For instance, quantified alternatives are rare among econometrics- or statistics-based papers. In contrast, they are studied in almost half of the papers using integrated or building energy models. It is more difficult to study the consequences of potential changes in technology adoption or behaviors with econometrics models, which are by nature designed to analyze the consequences of existing technologies and behaviors. In some papers, generic measures are studied (e.g. 'better insulation'), whereas in other papers specific actions are documented (e.g. 'mixed mode ventilation'). A direct comparison across the papers is therefore difficult.

3. Demand-side mitigation options vary across end-use sectors and are consistent with well-being

Key strategies include socio-behavioral change, low-carbon infrastructure and service provision, and rapid adoption of low-carbon technologies. These can be broadly mapped into ASI categories.

Demand side options are multifaceted and reach into every part of daily life. A wide array of different aspects are covered in the focus issue. Here, we start with considering an overview on consumption-based options from an individual perspective, then specify the urban contribution, followed by transport, building and food sector perspectives. This is the rounded up by circular economy (CE), material efficiency and digitalization specific reviews, exploring in each case demand-side mitigation options.

The systematic review 'Quantifying the potential for climate change mitigation of consumption options' investigates impacts of consumption options on climate change mitigation, based on a comprehensive screening of **consumption-based footprint studies** (Ivanova *et al* 2020). The study generated an initial sample of 11 626 references from Scopus and Web of Science. After removing duplicates and irrelevant studies, inter alia with the help of machine learning methods, the final sample consisted of 53 relevant studies. It identifies 60 consumption-based mitigation options, categorized in ASI categories, and estimates their potential, as based in the literature, with median and range values. The results can be seen as global benchmark, and are, for example, reflected in the Technical Summary of the IPCC report on climate solutions (Pathak *et al* 2022). A crucial next step is to harmonize consumption-based options as a function of income, culture, and spatial context.

Ivanova *et al* emphasize the importance of considering the full range of impacts of consumption options, including impacts on commuting travel, non-work travel, home energy use, and office energy use. While options appear at individual scale, there are multiple challenges, including technical, economic, and institutional barriers. Overcoming these barriers requires a combination of technological innovation, policy intervention, and behavioral change.

In the domain of transport, the options with the highest mitigation potential include:

1. Living car-free, which has the highest median mitigation potential across all of the reviewed options at 2.0 tCO_2eq/cap, with a range between 3.6 and 0.6 tCO_2eq/cap.
2. Reducing air travel. One less long return flight may reduce between 4.5 and 0.7 (mean of 1.9) tCO_2eq/cap, while taking one less medium return flight can reduce between 1.5 and 0.2 (0.6) tCO_2eq/cap. The two options have a median reduction potential of 1.7 and 0.6 tCO_2eq/cap, respectively.
3. Shifting to less carbon-intensive fuel sources, means, and modes of transportation.

In the context of food, the highest carbon savings come from dietary changes, particularly the adoption of a vegan diet with an average and median mitigation potential of 0.9 and 0.8 tCO_2eq/cap, respectively. In housing, main options include investments

⑪-1.AIT

AIT
Asian Institute of Technology

into heat pumps, prosumer renewable energy systems (including balcony solar for renters), and insulation measures.

The mitigation potentials strongly depend on income, as high-income households fly much more and have different consumption patterns. Affluent households not only have more potential to decarbonize their lifestyles, but also more responsibility and more capacity (Nielsen *et al* 2021).

Demand-side solutions are particularly relevant in **cities**, an insight relevant also for the upcoming special report on cities and climate change in Seventh Assessment Cycle of IPCC. The review 'Climate change mitigation in cities: a systematic scoping of case studies' provides an in-depth analysis of urban mitigation solutions and their potential for GHG abatement (Sethi *et al* 2020).

The study identifies demand-side management solutions, including peak shaving or shifting, energy efficiency measures, and retrofitting buildings, as the most frequently investigated interventions. These solutions are crucial for local climate mitigation. Sethi *et al* emphasize the active role of local governments in leading urban climate solutions, either through regulations or partnerships with private or non-governmental actors. Findings suggest that a mix of market mechanisms, user incentives, subsidies, and voluntary measures in cooperation with non-governmental actors is crucial for local climate mitigation.

The study finds that technology-based interventions are more prevalent, with 80% of urban climate solutions being technologically driven. However, it also highlights the importance of combining technological and social experiments to expand and upscale mitigation efforts in urban systems. The highest mitigation values are observed in buildings with net-zero emission buildings (105%), transportation with E-mobility (94%), and waste with waste to energy (87%). However, the performance of certain climate policies, such as the deployment of cool roofs, can vary significantly depending on location. Many of the case studies originated in Europe and China. Crucially, Sethi and colleagues also find that the scale of intervention controls mitigation potential at two levels. Interventions with smaller absolute scope demonstrate greater marginal mitigation potential than more system-wide interventions. The review concludes that urban climate research requires a fusion of disciplinary knowledge to better utilize quantitative and qualitative data on how cities could respond to global warming.

The review titled 'Determinants of low-carbon transport mode adoption: systematic review of reviews' focuses on the factors that influence the adoption of **low-carbon transport modes** (Javaid *et al* 2020). The authors conducted a systematic review of literature reviews, categorizing them into meta-analysis or traditional reviews. They extracted information across these different review types, differentiating between quantitative and qualitative studies. The data extraction process involved two steps: extracting information and judging the quality of information.

The study identified around 75 reviews that fulfilled all the necessary conditions. Thematically, most review studies are linked to infrastructure factors (59 reviews), whereas social factors are lacking in most cases (only 11 review studies). Individual-level factors are also relatively well represented with 32 reviews dealing with these factors. Most of the reviews cover studies from North America, Europe, and Australia. Only 20% of the reviews contain at least one study from Asia or Africa.

From an individual, social, and infrastructure perspective, the study finds that all three dimensions unambiguously interfere with mode choice. Individuals are most motivated to shift modes if they are well-informed, if personal norms match low-carbon mode use, and, most importantly, if they perceive to have personal control over decisions. Perceptions about common travel behavior (descriptive social norms), especially if supported by perceived normative beliefs of others (injunctive norms), are highly influential to support mode shift.

However, the overall margin of shift as induced by individual and social settings remains limited. Instead, the infrastructure factors explain large differences in mode choice. New shared mobility modes, and teleworking and shopping, add a long tail to modes chosen, but are no game changer. The study concludes that a transition to low-carbon mobility requires low-carbon infrastructure, which leverages enthusiastic individuals' concerns and empowers them for mode change, and that address safety concerns prevalent especially in cities of the Global South. The mode shift to low-carbon option can then be sustained and enhanced by social influence in the form of collective social norms.

A more detailed issue is mobility patterns, and in particular the case of avoiding commuting altogether by **teleworking**, an issue that gained increased traction with COVID-19. Accordingly, 'A systematic review of the energy and climate impacts of teleworking' provides a comprehensive investigation of the impacts of teleworking on energy consumption and climate change (Hook *et al* 2020). The study generated an initial sample of 11 626 references from Scopus and Web of Science. After removing duplicates and irrelevant studies, the final sample consisted of 39 relevant studies. The majority of the studies (26 out of 39) suggest that teleworking leads to a net reduction in energy use and/or emissions, with only five studies finding a net increase. These benefits largely result from the elimination of the commute, reductions in congestion, and reductions in office-based energy

⑪-1.AIT

AIT
Asian Institute of Technology

consumption. A related review, not in this focus issue, suggests that travel related rebound effects can consume up to one fifth of the emission savings, which still clarifies that telecommuting is largely beneficial to the environment and climate change (Hostettler Macias *et al* 2022).

Hook and coauthors emphasize the importance of considering the full range of impacts of teleworking, including impacts on commuting travel, non-work travel, home energy use, and office energy use, pointing out that the potential for energy and emission reductions through teleworking is often overlooked in climate policy. They conclude that overcoming barriers to telecommuting requires a combination of technological innovation, policy intervention, and behavioral change.

The study 'A map of roadmaps for zero and low energy and carbon buildings worldwide' provides a comprehensive overview of global efforts towards achieving **zero and low energy and carbon buildings** (ZLECB) (Érika Mata *et al* 2020). It maps and classifies 117 roadmaps, policies, and plans from 37 countries. The majority of the documents focus on more developed regions (76% or 325 documents), including Europe subregions, USA & Canada, and Australia & New Zealand. Only 4% of the documents have global coverage.

The most frequent types of documents are recommendations made by researchers and academics to inform policymakers and performance assessment case studies done to establish design practices or prove the efficiency of demonstration projects. The policy objectives include increasing the energy efficiency of new and existing buildings and appliances, encouraging energy distribution companies to support emission reduction from the building sector, targeting attitudes and behavior change, and substituting fossil fuels (FF) with renewable energy sources (RES).

As key demand-side measures, the review specifies the need for effective building design, efficient technical systems, on-site production from RES, and low impact material choices to achieve low energy and carbon during a building's lifecycle. Mata and colleagues identify evidence gaps and clusters, suggesting areas for future research and potential for synthesis via full systematic reviews and emphasize the need for a comprehensive understanding of current efforts, including which measures work and which do not, to avoid wasting funding and resources.

As an accompanying review, 'Systematic map of determinants of buildings' energy demand and CO_2 emissions shows need for decoupling' provides a systematic mapping of the literature on determinants of **energy demand** and CO_2 emissions from **buildings** (Mata *et al* 2021). The authors identify 376 relevant studies and highlight gaps in terms of the studied variables, geographical scope, and methodological approach. The study confirms that worldwide, income, energy price, and outdoor temperature are unequivocal drivers of buildings' energy demand and CO_2 emissions, followed by other indicators of scale such as population or heated floor area. The authors emphasize that decoupling from rising wealth levels has not been observed, which will continue to challenge reductions in energy use and CO_2 emissions from buildings in line with climate targets.

In terms of demand-side climate change mitigation, the study suggests that macroeconomic policies focusing on the impacts of income, energy price, population, and growing floor area are needed in combination with technical policy to reduce the impact of outdoor climate. The authors argue that a comprehensive understanding of the key factors behind buildings' energy use can serve as a basis to define the policy actions most suited to drive the decarbonization of the building sector.

Food stands out as where the largest demand-side potential for GHG emission reduction is located, particulary in diet shift from meat to plant-based diets (Creutzig *et al* 2022a). Correspondingly, the review 'Climate change mitigation through dietary change: a systematic review of empirical and modeling studies on the environmental footprints and health effects of 'sustainable diets' is another important contribution to this focus issue (Jarmul *et al* 2020).

The review systematically investigates the role of dietary changes in climate change mitigation. The authors highlight that the global food system contributes 21%–37% of global GHG emissions, and its impact on the environment is expected to increase substantially by 2050, largely due to population growth and dietary change, particularly in rapidly transitioning economies.

The study identifies the adoption of diets with low environmental impact, often referred to as 'sustainable diets', as an important climate change mitigation strategy. These diets are typically high in plant-sourced foods and low in animal-sourced and processed foods. The review found that switching to 'sustainable diets' results in an average 25.8% reduction in GHG emissions, with vegan diets leading to the largest reduction (approximately 70.3%). However, it also noted an increase in water use associated with these diets. The research is based on 18 studies, encompassing 412 measurements, and highlights the substantial potential for dietary changes to contribute to climate change mitigation and improve health outcomes. The relationship between food systems and climate change is bi-directional, and climate change is currently affecting yields of crops and livestock products and is projected to continue to do so in the future. Hence, demand-side options, such as dietary shifts, can also help to better allocate scarce land resources to human nutrition. Overall, changes in consumer behavior, specifically dietary choices, but

AIT
Asian Institute of Technology

also food waste reduction, can contribute to mitigating climate change at a highly relevant scale.

What can the CE contribute to climate change mitigation? 'Saving resources and the climate? A systematic review of the CE and its mitigation potential' provides a systematic review of the literature on the CE and its potential for climate change mitigation (Cantzler *et al* 2020). The authors conducted a comprehensive literature review, identifying 3244 studies initially, of which 341 (10%) were deemed relevant based on specific mitigation references. The studies were then synthesized and categorized based on sector, geography, resolution, and CE principles.

The document discusses the challenges of synthesizing the mitigation potential of the studies due to the use of different baselines, metrics, and indicators. There is a lack of standardization in the understanding and application of the CE concept, leading to a wide array of measures under the CE umbrella. While the CE concept may serve as a communication tool to accelerate policy action, there is a need for transparency and clarity in its use to avoid confusion and ensure effective climate change mitigation efforts.

Material efficiency is a key CE strategy, relating to demand-side change also within industry. 'Material efficiency strategies to reducing GHG emissions associated with buildings, vehicles, and electronics—a review' presents an extensive review of strategies to enhance material efficiency and reduce GHG emissions (Hertwich *et al* 2019). The authors find that material efficiency could reduce GHG emissions by 12%–21% in the construction sector, 26%–31% in the vehicle sector, and 14%–53% in the electronics sector.

The potential for GHG reduction in the construction sector is mainly due to the reduction in the use of concrete and steel, which are the most emission-intensive materials. In the vehicle sector, lightweight design, car sharing, and longer vehicle lifetimes could significantly reduce emissions. In the electronics sector, the extension of product lifetimes, and the reuse and recycling of components, could lead to significant emission reductions.

Hertwich and colleagues emphasizes the importance of policy interventions to promote material efficiency. The potential for emission reductions through material efficiency remains often overlooked in climate policy. Hence, material efficiency strategies should be integrated into the broader framework of climate policy to achieve significant emission reductions.

On consumer side, it has been long speculated that **digitalization** provides efficiency gains in end use. The review titled 'Digitalization of goods: a systematic review of the determinants and magnitude of the impacts on energy consumption' provides a comprehensive review of the impacts of digitalization on energy consumption (Court and Sorrell 2020), focusing on five categories of goods or services that have been digitalized: e-publications (books, magazines, and journals), e-news, e-business, e-music, and e-videos and games. The study employs a systematic review methodology, including a comprehensive search of literature, screening of titles and abstracts, full-text screening, and data extraction. The search phase generated an initial sample of 12 849 references, which after removing duplicates and irrelevant studies, resulted in a final sample of 31 relevant studies.

The review identifies several examples of potential energy savings due to digitalization in specific technologies. For instance, in the case of e-publications, there's a notable reduction in energy consumption compared to physical books, depending on user behavior and device efficiency. Similarly, digitalization in music and news industries shows a trend towards energy savings when compared to traditional media formats. These savings are context-dependent and vary based on factors like device usage, energy sources, and the displacement of non-digital activities.

4. Behavioral and social interventions and initiatives to reduce GHG emissions

Another set of reviews in the focus section complements demand-side mitigation options with a view on behavioral and social interventions and approaches—society perspectives—on climate change mitigation, revealing the relevance of understanding motivations and rationalities of people both as consumers and as social actors and citizens.

The review titled 'Effectiveness of behavioral interventions to reduce household energy demand: a scoping review' provides a comprehensive review of **behavioral interventions** aimed at reducing household GHG emissions (Composto and Weber 2022).

The authors have conducted a scoping review of 584 empirical papers. The most studied behavioral interventions are providing timely feedback and reminders (258 papers) and making information intuitive and easy to access (246), followed by communicating a norm (158). Electricity use is the most studied target behavior (439 papers), followed by investments in energy efficiency (94), choice in mode of transportation (41), choice of energy source (17), and buying carbon offsets (4).

Similar to other reviews in these focus issue, the authors categorize behavioral changes into three types: ASI. Avoid responses are examined in the most papers (415 papers), followed by shift (112) and improve (77) responses. 72 of the 584 papers included an economic incentive; the choice architecture interventions of reframing consequences (26%) and setting proper defaults (24%) are most frequently combined with an economic incentive. The authors

⑪-1.AIT

AIT
Asian Institute of Technology

also discuss the methodological aspects of the studies reviewed, noting the presence of publication bias and the need for larger sample sizes, random assignment, control groups, and field applications. They also highlight the need for future research to routinely measure longer-term impacts of interventions.

Another review and meta-analysis, titled 'Meta-analytic evidence for a robust and positive association between individuals' pro-environmental behaviors and their subjective wellbeing' (Zawadzki *et al* 2020), explores the relationship between individuals' **pro-environmental behaviors** and their subjective well-being. Such behaviors, which are crucial for reducing carbon emissions, can have a significant impact on people's daily lives. The review investigates whether and how individuals' pro-environmental behavior is related to subjective wellbeing, and whether pro-environmental behaviors can be promoted in a way that protects and promotes individuals' subjective wellbeing.

The review finds that fostering pro-environmental behaviors among individuals can be a key strategy for reducing GHG emissions. The relationship between pro-environmental behaviors and subjective wellbeing is positive and robust. This implies that individuals who engage in pro-environmental behaviors tend to experience higher levels of subjective wellbeing. The authors suggest that this relationship may be due to the meaningfulness of pro-environmental behaviors. Specifically, behaviors that are consciously decided and clearly meaningful at the time of performance, such as sustainable purchase decisions, are associated with higher levels of subjective wellbeing. Similarly, indicators of subjective wellbeing that reflect personal meaning, such as a sense of 'warm glow' or eudaimonic happiness, are also strongly related to pro-environmental behavior.

The authors point outs that policymakers can leverage this relationship to design 'win-win' sustainability programs that not only positively impact the environment but also enhance people's subjective wellbeing. It may be beneficial to emphasize how pro-environmental behaviors can enhance, rather than detract from, people's subjective wellbeing to maintain public engagement with pro-environmental programs or policies. Future studies could test which strategies are most effective in emphasizing the meaning of pro-environmental behavior, and to make people aware of the beneficial effects of pro-environmental actions on subjective wellbeing.

In a shift of gear, the review titled 'Is working less really good for the environment? A systematic review of the empirical evidence for resource use, GHG emissions and the ecological footprint' provides a comprehensive review of the relationship between **working time** reduction (WTR) and environmental impacts (Antal *et al* 2021). The authors conducted a systematic review of the literature, including full-text screening, citation snowballing, and coding based on pre-developed criteria. The review identified 15 fully relevant research articles, which were then critically appraised and synthesized.

The document discusses the empirical literature on working time, resource use, and emissions, with a focus on country-level studies that use econometric approaches to investigate the relationship between aggregate working time and environmental indicators. The review found that while WTR can lead to reduced GHG emissions and resource use, the outcomes are highly context-dependent. The environmental benefits of WTR are primarily through decreased incomes and consumption expenditures. However, the study also notes significant variations in results due to different methodologies and indicators used across studies, making it challenging to draw definitive conclusions.

The desire for **status** can drive unsustainable consumption, but also motivate acquiring energy saving goods and services. The review titled 'Status consciousness in energy consumption: a systematic review' explores the relationship between status and energy consumption, and how this relationship can be leveraged for climate change mitigation (Ramakrishnan and Creutzig 2021). The authors conducted a comprehensive review of existing published work that links status to household consumption decisions and behavior across all end-use sectors. They screened 2662 papers and fully reviewed 53 papers that complied with their criteria.

The review identified 23 distinct theories, with the literature most frequently referring to Veblen's theory of conspicuous consumption. The authors also detailed estimations of status-related energy consumption and identified studies that quantitatively relate status to energy-saving behavior or decisions, and studies that relate status to increased emissions. Status can explain up to 20% change in consumption levels or the willingness-to-pay for carbon reducing consumption.

Interestingly, the authors found that major status-related consumption decisions, such as for housing and big cars, are hardly captured by the literature that relates status consumption to energy use and GHG emissions. This is a considerable gap in the literature, omitting major sources of status-related decisions with high carbon footprint.

The paper concludes that framing energy-saving behavior as high status is a promising strategy for emission reduction. Progressive taxation of status items, such as floor space and vehicle size, can effectively internalize the positional externalities and signal social undesirability, but also reduce emissions.

The review titled '**Lifestyle changes** in mitigation pathways: policy and scientific insights' systematically

⑪-1.AIT

AIT
Asian Institute of Technology

investigates the relevance of demand-side measures from individual, social, and infrastructure perspectives regarding GHG emission reduction (Saujot *et al* 2020).

The authors argue that changes in lifestyle, driven by individual and societal choices, can create the necessary space for a feasible supply-side decarbonisation within a 1.5 °C emission budget without the need for negative emissions. This implies that demand-side measures, such as changes in consumption patterns and behaviors, can significantly contribute to GHG emission reduction. The review also highlights the importance of policies that influence future lifestyles, their cost-effectiveness, their consequences on well-being, and their legitimacy. Most of the pathways reviewed do not satisfactorily investigate these aspects. Human and social sciences have a lot to say about understanding changes in lifestyles, including their drivers (e.g. household life-cycle, values), constraints (e.g. infrastructure lock-in, social norms), and the dynamics at play.

The study also acknowledges the political nature of mitigation pathways and argues that this should not preclude lifestyle changes from consideration in pathway development. Saujot and colleagues believe that most changes related to technologies and to the socio-technical system are not value-neutral and that acknowledging this can help in developing more effective and acceptable mitigation strategies.

The study 'Movements shaping climate futures: a systematic mapping of protests against FF and low-carbon energy (LCE) projects' provides a comprehensive analysis of protests against both FF and LCE projects (Temper *et al* 2020). It finds that place-based movements are successful in curbing both FF and LCE projects, with over a quarter of projects encountering social resistance being shelved, suspended, or delayed. The research highlights that LCE projects are almost as conflictive as FF projects, with 30% of FF conflicts and 26% of LCE projects being high intensity. Both project types particularly impact vulnerable groups such as rural communities and Indigenous peoples, with Indigenous peoples involved in 58% of the cases analyzed.

Among LCE projects, hydropower was found to be particularly socially and environmentally damaging, leading to mass displacement and large-scale ecosystem transformation. Incidents of repression or violence against protesters and land defenders occurred in one third of cases, with violent responses most common in hydropower, biomass, pipelines, and coal extraction conflicts. Ten percent of all cases involved the assassination of activists.

The study also highlights 'sacrifice zones' in both the FF and the emerging LCE economies. These zones are areas disproportionately affected by environmental hazards and polluting activities due to industrial, extractive, or infrastructural projects. Specific examples include regions affected by coal mining, oil and gas extraction, and hydraulic fracturing. These areas often face significant environmental degradation, health risks, and social and economic impacts. The study highlights that these sacrifice zones are frequently located in marginalized communities, underscoring issues of environmental justice and inequality. The review also identifies the claims and demands coming from project-impacted communities for a socio-environmental justice approach in building low-carbon futures. The data suggests that the energy transition and decarbonization risk producing similarly unequal social burdens unless there is a deeper transformation of the energy system, informed by engagement and co-design with communities on the energy futures they want. Without community engagement and co-design in shaping energy futures, the transition to LCE may reproduce the social inequalities seen in the FF economy.

Last but not least, a review on 'Limiting food waste via grassroots initiatives as a potential for climate change mitigation: a systematic review' focuses on the role of **grassroots** initiatives in reducing food waste and thereby mitigating climate change (Mariam *et al* 2020). From a quantitative perspective, the study found that grassroots initiatives have the potential to reduce GHG emissions by 4.3%–8.2% of the food sector's emissions. This reduction is equivalent to 0.3%–0.6% of total global emissions. The study also found that these initiatives could potentially reduce food waste by 30%–46%.

From a qualitative perspective, the study highlights the importance of grassroots initiatives in fostering a culture of sustainability and reducing food waste. These initiatives often involve local communities and individuals, and they can have a significant impact on social norms and behaviors related to food consumption and waste. By engaging individuals and communities in efforts to reduce food waste, these initiatives can help shift consumption patterns and social norms in a more sustainable direction. Moreover, they can also contribute to the development of infrastructure and systems for reducing food waste, such as food sharing platforms and community gardens. Thus, grassroots initiatives can have significant impacts not only at the individual and community levels but also in terms of broader social and infrastructural changes.

5. Outlook

We here present a comprehensive overview of 22 review papers on demand-side climate change mitigation, highlighting the significant potential of demand-side approaches to complement technology-focused solutions, and emphasizing their contribution to well-being and planetary stability. This systematic and extensive reviews underscore the

⑪-1.AIT

AIT
Asian Institute of Technology

essential role of demand-side strategies in achieving climate goals, particularly in the context of the Paris Agreement's objectives. By choosing to aggregate a complete focus issue with systematic reviews and meta-analysis, we here synthesize crucial evidence relevant to understanding of demand-side mitigation's role in climate change efforts.

Forward looking, we suggest that research on demand-side climate solutions should fill gaps in the when, who, how, and where.

When: studying history and narratives can reveal how various societies and cultures have historically implemented practices akin to demand-side climate mitigation and when they shifted away. By examining historical lifestyles, consumption patterns, and social norms, researchers can identify instances where communities naturally engaged in low-impact living, resource conservation, or sustainable practices. Historical examples can provide insights into successful implementation strategies, the role of cultural values in shaping consumption, and the potential for societal adaptation. For example, traditional lifestyles in the Amazonian rainforest strived for harmony with ecosystems and biodiversity and, while impossible to transfer to modern lifestyles, can provide guidance on strategies and mindsets. Historical narratives can also show at what junctures human societies moved away from sustainable to non-sustainable practices.

Who: studies on the political economy of demand-side measures are crucial for understanding how economic and political structures, power relations create role models, influence lifestyle choices and consumption patterns. They shed light on the vested interests that may create a social hierarchy and interdependence that resist changes promoting sustainable living, offering insights into the dynamics that impede the adoption of climate-friendly lifestyles. Key examples include the FF industry, but also intermediate industries, such as suppliers for car manufacturers. Studies may help to identify barriers and develop strategies to overcome resistance from entities benefiting from the status quo.

How: the design of the 'how of the transition' in demand-side solutions for climate change requires an interdisciplinary, full-system perspective. This involves coordinating various elements such as economic incentives, regulatory frameworks, sociocultural changes (including the influence of religions and identities), and the role of physical infrastructures and the built environment. Such an approach needs to be sequenced and coordinated, transcending the scope of individual disciplines or sometimes collaborative disciplinary approaches. Investigating these complex interactions in a controlled setting is challenging if not impossible, but research from a systems' view is nonetheless needed. Technosphere concepts, such as automobility, digitalization, and energy systems, may be in the center of these investigations. This necessitates more collaborative research across disciplines to understand and implement effective demand-side solutions.

Where: the systematic reviews in this focus issues, similarly to other reviews and systematic maps on, for example, cities (Lamb *et al* 2019), is unambiguous in that studies on the Global South are missing. Also, in global south rural density and interdependence of cities and rural geographies and interdependence of formal and informal economies deserve a special attention to avoid uncontrolled penetration of unsustainable practices among new consumer groups. However, as developing countries are still urbanizing and growing in terms of economic activities, studies are urgently needed that explore and substantiate how demand for better services can be provisioned and satisfied, bringing low emissions together with high quality of life.

ORCID iDs

Felix Creutzig https://orcid.org/0000-0002-5710-3348
Joyashree Roy https://orcid.org/0000-0002-9270-8860
Jan Minx https://orcid.org/0000-0002-2862-0178

References

Andrew H, Court V, Sovacool B K and Sorrell S 2020 A systematic review of the energy and climate impacts of teleworking *Environ. Res. Lett.* **15** 093003
Antal M, Plank B, Mokos J and Wiedenhofer D 2021 Is working less really good for the environment? A systematic review of the empirical evidence for resource use, greenhouse gas emissions and the ecological footprint *Environ. Res. Lett.* **16** 013002
Cantzler J, Creutzig F, Ayargarnchanakul E, Javaid A, Wong L and Haas W 2020 Saving resources and the climate? A systematic review of the circular economy and its mitigation potential *Environ. Res. Lett.* **15** 123001
Composto J W and Weber E U 2022 Effectiveness of behavioural interventions to reduce household energy demand: a scoping review *Environ. Res. Lett.* **17** 063005
Court V and Sorrell S 2020 Digitalisation of goods: a systematic review of the determinants and magnitude of the impacts on energy consumption *Environ. Res. Lett.* **15** 043001
Creutzig F *et al* 2018 Towards demand-side solutions for mitigating climate change *Nat. Clim. Change* **8** 260–3
Creutzig F *et al* 2021 A typology of 100,000 publications on demand, services and social aspects of climate change mitigation *Environ. Res. Lett.* **16** 033001
Creutzig F *et al* 2022a Demand-side solutions to climate change mitigation consistent with high levels of well-being *Nat. Clim. Change* **12** 36–46
Creutzig F *et al* 2022b Chapter 5—Demand, services and social aspects of mitigation *Climate Change 2022: Mitigation of Climate Change* (Cambridge University Press)
Creutzig F, Fernandez B, Haberl H, Khosla R, Mulugetta Y and Seto K C 2016 Beyond technology: demand-side solutions for climate change mitigation *Annu. Rev. Environ. Resour.* **41** 173–98

⑪-1.AIT

AIT
Asian Institute of Technology

Creutzig F, Hilaire J, Nemet G, Müller-Hansen F and Minx J C 2023 Technological innovation enables low cost climate change mitigation *Energy Res. Soc. Sci.* **105** 103276

Haberl H *et al* 2020 A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, Part II: synthesizing the insights *Environ. Res. Lett.* **15** 065003

Hertwich E G, Ali S, Ciacci L, Fishman T, Heeren N, Masanet E, Asghari F N, Olivetti E, Pauliuk S and Qingshi T 2019 Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review *Environ. Res. Lett.* **14** 043004

Hostettler Macias L, Ravalet E and Rérat P 2022 Potential rebound effects of teleworking on residential and daily mobility *Geogr. Compass* **16** e12657

Ivanova D, Barrett J, Wiedenhofer D, Macura B, Callaghan M and Creutzig F 2020 Quantifying the potential for climate change mitigation of consumption options *Environ. Res. Lett.* **15** 093001

Jarmul S, Dangour A D, Green R, Liew Z, Haines A and Scheelbeek P F D 2020 Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of 'sustainable diets *Environ. Res. Lett.* **15** 123014

Javaid A, Creutzig F and Bamberg S 2020 Determinants of low-carbon transport mode adoption: systematic review of reviews *Environ. Res. Lett.* **15** 103002

Lamb W F *et al* 2021 A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018 *Environ. Res. Lett.* **16** 073005

Lamb W F, Creutzig F, Callaghan M W and Minx J C 2019 Learning about urban climate solutions from case studies *Nat. Clim. Change* **9** 279–87

Mariam N, Valerie K, Karin D, Angelika W-R and Nina L 2020 Limiting food waste via grassroots initiatives as a potential for climate change mitigation: a systematic review *Environ. Res. Lett.* **15** 123008

Mata É, Korpal A K, Cheng S H, Jiménez Navarro J P, Filippidou F, Reyna J and Wang R 2020 A map of roadmaps for zero and low energy and carbon buildings worldwide *Environ. Res. Lett.* **15** 113003

Mata É, Wanemark J, Cheng S H, Ó Broin E, Hennlock M and Sandvall A 2021 Systematic map of determinants of Buildings' energy demand and CO_2 emissions shows need for decoupling *Environ. Res. Lett.* **16** 055011

Nachtigall F, Wagner F, Berrill P and Creutzig F 2023 The built environment and induced transport CO_2 emissions: a double machine learning approach to account for residential self-selection (arXiv:2312.06616v1)

Nielsen K S, Nicholas K A, Creutzig F, Dietz T and Stern P C 2021 The role of high-socioeconomic-status people in locking in or rapidly reducing energy-driven greenhouse gas emissions *Nat. Energy* **6** 1011–6

Pathak M, Slade R, Pichs-Madruga R, Ürge-Vorsatz D, Shukla P R, Skea J, Abdulla A, Al Khourdajie A, Babiker M and Bai Q 2022 Working group III contribution to the IPCC sixth assessment report (AR6)(Technical summary)

Quéré C L, Ivar Korsbakken J, Wilson C, Tosun J, Andrew R, Andres R J, Canadell J G, Jordan A, Peters G P and van Vuuren D P 2019 Drivers of declining CO_2 emissions in 18 developed economies *Nat. Clim. Change* **9** 213–7

Ramakrishnan A and Creutzig F 2021 Status consciousness in energy consumption decisions: a systematic review *Environ. Res. Lett.* **16** 053010

Roy J, Some S, Das N and Pathak M 2021 Demand side climate change mitigation actions and sdgs: literature review with systematic evidence search *Environ. Res. Lett.* **16** 043003

Saujot M, Le Gallic T and Waisman H 2020 Lifestyle changes in mitigation pathways: policy and scientific insights *Environ. Res. Lett.* **16** 015005

Sethi M, Lamb W, Minx J and Creutzig F 2020 Climate change mitigation in cities: a systematic scoping of case studies *Environ. Res. Lett.* **15** 093008

Skea J, Shukla P, Reisinger A, Slade R and Pathak M 2022 *Climate Change 2022. Mitigation of Climate Change. Summary for Policymaker* (IPCC)

Temper L *et al* 2020 Movements shaping climate futures: a systematic mapping of protests against fossil fuel and low-carbon energy projects *Environ. Res. Lett.* **15** 123004

Viguié V, Juhel S, Ben-Ari T, Colombert M, Ford J D, Giraudet L G and Reckien D 2021 When adaptation increases energy demand: a systematic map of the literature *Environ. Res. Lett.* **16** 033004

Wiedenhofer D *et al* 2020 A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping *Environ. Res. Lett.* **15** 063002

Zawadzki S J, Steg L and Bouman T 2020 Meta-analytic evidence for a robust and positive association between individuals' pro-environmental behaviors and their subjective wellbeing *Environ. Res. Lett.* **15** 123007

⑪-1.AIT

The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/1759-5908.htm

Improving community resilience through distributed solar energy as critical infrastructure – a case study of South Asia

Parimita Mohanty
United Nations Environment Programme (UNEP), Asia Pacific Office, Bangkok, Thailand

Indrajit Pal
Disaster Preparedness, Mitigation and Management (DPMM), Asian Institute of Technology, Bangkok, Thailand, and

Joyashree Roy
Asian Institute of Technology, Bangkok, Thailand

Received 19 February 2023
Revised 31 January 2024
Accepted 2 April 2024

Abstract

Purpose – The analytical framework proposed in this study aims to link the capital portfolio approach to sustaining human well-being, 2015 sustainable development goals and development action ARC-D concepts. Nepal case study is a "tribrid" power generation system that combines distributed solar, hydro and wind power generation capacities for the resilience of a community of around 500 people in a remote village with a total installed capacity of 28 kW. The second case study is about the solarization of 900 health centres in Chhattisgarh, India, with off-grid solar PV with a cumulative capacity of 3 MW.

Design/methodology/approach – Critical infrastructure at the community scale needs to be resilient to maintain community-level functionality in the face of adverse impacts. The present study provides two case study sites from Nepal and India to demonstrate various elements of resilience building for critical infrastructures, especially for the energy sector.

Findings – Granular technology and distributed generation in Nepal and India can act as critical infrastructure in providing on-demand electricity service to enhance community-level resilience along with future opportunities of scale up.

Joyashree Roy acknowledges funding support under EDIT-AIT project. EDIT-AIT project at the Asian Institute of Technology, Thailand, received funding from the Energy Demand Changes Induced by Technological and Social Innovations (EDITS) project, which is part of the initiative co-ordinated 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]. Indrajit Pal acknowledges funding support under the Coalition of Disaster Resilient Infrastructure (CDRI) fellowship (first cohort 2021–2022) of application number 210117487 and the climate innovation solution "Climate Resilient Infrastructure for Social Transformation and Adaptation (CRISTA)" supported under the Asian Disaster Preparedness Centre (ADPC) Climate Innovation Challenge (CIC), funded by FCDO-UKAID and The World Bank.

International Journal of Disaster Resilience in the Built Environment
© Emerald Publishing Limited
1759-5908
DOI 10.1108/IJDRBE-02-2023-0039

Originality/value – The analytical framework for evaluating community-scale resilience through critical infrastructure design and application of the framework using evidence based on case studies are the original contributions.

Keywords Modern energy, Access to electricity, Enabling investment, Granular technology, Vulnerability and resilience, Distributed electricity generation

Paper type Case study

1. Introduction

In this paper, "community resilience" refers to "uninterrupted access to on-demand electric power supply of a community to enable the community members to maintain individual and collective functionality despite external shocks". Enhancing community resilience through delivery of uninterrupted energy service access ensures multidimensional well-being of the various stakeholders: people and businesses. Infrastructures which enable access to uninterrupted functionality of basic services for a decent living (Rao *et al.*, 2019) to protect the material well-being of members of the community are defined as "critical" in this paper.

One frequent external shock is extreme weather events (Pal and Bhatia, 2017; IPCC, 2018; Roy *et al.*, 2021a, 2021b) and associated power outages due to the direct impact on power infrastructure, primarily through damage of transmission lines or sometimes damage to the small substations in the power supply chain. Power outages interrupt basic functionality in a community through disruption in services like street lighting for the public good, water supply, cooling and heating services, refrigeration service needed both at the household level or in the health centres.

The paper addresses the research question: can community resilience be enhanced through distributed energy supply systems (Lwin *et al.*, 2020; Hasselqvist *et al.*, 2022) which need smaller, modular distribution networks with the opportunity to provide flexibility in innovation, investment, installation and operation, compared to the capital intensive, large technological installations that create long term lock-in impacts?

Over the years, many cities in India, Bangladesh, Cambodia, Thailand (Sothea and Oanh, 2019) and other parts of the region (Peerapong and Limmeechokchai, 2017) households, commercial centres and residential complexes have maintained day-to-day functions by individually owned backup power units which are run mostly by fossil fuels or batteries. However, in recent years, there has been a surge in the deployment of distributed solar mini-grids (Chakravarty and Joyashree Roy, 2021; Mohanty *et al.*, 2019; Sharma *et al.*, 2014) and energy storage systems, which promote uninterrupted power supply to the community's critical facilities such as shelters and household chores, health and medical facilities, communications infrastructure and public safety when the electrical grid system fails. Solar PV-based technology deployment, which has inherent granularity and modularity (Mongabay, 2021), has the potential to enhance the community's resilience with multiple co-benefits such as productivity improvement, carbon emissions reduction potential, local job creation through energy service delivery, local entrepreneurship development of a community to enhance disaster preparedness and emergency operations. There are several interventions already in operation in the Asia Pacific region, such as solar power projects in cyclone shelters of Cox's Bazar, Bangladesh by the World Food Programme (Mehelin, 2020); solar projects installed in public health centres (PHCs) in India and Pakistan, solar portable drinking water system for disaster impacted areas to understand these efforts through a resilience-building lens to help replicate for scale-up (Firstpost, 2021; Aditya Ramji *et al.*, 2017).

This paper consolidates the findings and the best practices from two case studies from India and Nepal, where a distributed solar system is used to provide critical community-scale infrastructure facilities with an uninterrupted power supply to enhance community resilience. Based on learnings from these case studies, the paper discusses what enabling conditions through policy and financing strategies make such interventions successful in resilience building in the face of extreme weather events. The paper focuses exclusively on how distributed solar PVs with battery storage systems protect critical infrastructure, which helps protect the functionalities of basic decent living services in the event of a large-scale power outage as an outcome of a disaster.

2. Analytical framework

Resilience that reflects risk and vulnerability is defined in a variety of ways depending on the context and whose resilience is under consideration. Resilience building for the poor to reduce their vulnerability and exposure to climate-related disasters is a well-established need (Hishan *et al.*, 2021). Social resilience has been at the centre of the discussions in the literature as a way to reduce the magnitude of disaster-related consequences (Marshall and Marshall, 2007; Lwin *et al.*, 2020; Patel *et al.*, 2017; Obrist *et al.*, 2010). A general definition of resilience was published by the National Academies Press, referring to resilience as "the ability to prepare and plan for, absorb, recover from and more successfully adapt to adverse events" (Sharifi, 2016; Sharifi and Yamagata, 2016). The involvement of local communities is fundamental and key to establishing a sustainable and functional early warning system to enhance the capacity for social resilience (Mohanty *et al.*, 2019). The recognition of the continuing vulnerability of communities to a range of multiple hazards needs attention on the capacity building of communities to assess and manage their own risk (Pal *et al.*, 2017).

If people and the attainment of their well-being are at the centre of any solution, then given the current levels of inequality, procedural justice demands faster provision of modern energy sources to all (Roy *et al.*, 2021a, 2021b). This is reflected in the 2015 sustainable development goals (SDGs) (United Nations, 2015). The question is how to meet the dual goal of climate action and modern energy access to enhance the resilience of vulnerable communities. A more fundamental question is how a genuine investment approach (Roy *et al.*, 2021a, 2021b; Roy *et al.*, 2021a, 2021b) can provide a non-declining productive base to ensure the flow of services to the community and the economy and hence build resilience (Roy *et al.*, 2021a, 2021b). It means to build a non-declining productive base, be it for a community, a country or a household and necessitates the maintenance of a capital portfolio, which is also consistent with the sustainable development concept (Hanley *et al.*, 1997).

In this paper, we combine the conceptual framework (Roy *et al.*, 2021a, 2021b), which connects disaster resilience and human well-being, the 2015 SDG framework and the ARC-D framework (analysis of resilience of communities to disaster, ARC-D toolkit, 2016) to provide a structure for evaluating interventions that support community resilience. With this framing of resilience, the authors try to show what components from a system perspective any long-term resilience-building project must have and towards mainstreaming community's development programmes.

The conceptual framework can be operationalised by the community resilience indicators mentioned below in Table 1, which can help examine how distributed renewable energy-based critical infrastructure can contribute to community resilience.

3. Case studies

Two cases from India and Nepal, using the distributed solar system, are presented as means for testing and using the analytical framework to assess long-term community resilience. The information collected through secondary search and from the primary sources through

Community resilience indicators	Questions to be answered	Link to SDGs
Measures to strengthen social and institutional capital		
Community decision-making; inclusion of vulnerable groups; participation of women	Is the community leadership committed, effective and accountable? Are the vulnerable groups in the community included and represented in community decision-making	SDG 1 Indicator 1.1.1 Indicator 1.3.1 SDG 5 Indicator 5.1.1 SDG 10 Indicator 10.4
Access to market	Has the local market grown with energy services and linked for products, labour and services protected against shocks?	SDG 7 Indicator 7.1.2 Indicator 7.2.1
Access to financial services	Whether formal or informal, are there affordable and flexible financial services (savings and credit schemes, microfinance)?	SDG 8 Indicator 8.3.1 Indicator 8.5.1
Social protection; social cohesion and conflict prevention	Does the community have access to informal and formal social protection schemes that support disaster risk reduction and recovery? Is there a sense of peace, security and effective conflict prevention and mitigation mechanisms, both within the community and with other communities?	SDG 1 Indicator 1.1.1 Indicator 1.3.1 SDG 5 Indicator 5.1.1 SDG 10 Indicator 10.4
Leadership and volunteerism in response and recovery	Does the community play a leading role in co-ordinating preparedness, response and recovery, reaching all affected people including the most vulnerable through organized and trained volunteers?	SDG 1 Indicator 1.5.1 Indicator 1.5.3 SDG 13 Indicator 13.1.1
Measures to strengthen knowledge capital		
Scientific risk assessment	Does the community combine local knowledge and risk perceptions with scientific knowledge, data and assessment methods?	SDG 1 Indicator 1.5.3 SDG 9 Indicator 9.5.2 SDG 13 Indicator 13.1.1
Education of children on DRR; rights awareness and advocacy	Have community members been exposed to/have participated in DRR specific awareness events (campaigns, discussions and training) and have improved awareness and practices as a result?	SDG 4, Indicator 4.1.1 Indicator 4.3.1 Indicator 4.4.1 SDG 9 Indicator 9.5.2
Measures to strengthen natural capital		
Sustainable environmental management; water security and management	Does the energy infrastructure help the community adopt sustainable environmental management practices that reduce disaster risk and new risks related to climate change? Does the community have access to sufficient water quantity and quality for domestic needs during disasters?	SDG 6 Indicator 6.1.1 Indicator 6.2.1 Indicator 6.4.2 SDG 7 Indicator 7.1.2
Measures to strengthen human capital		
Health access and awareness	Does the energy infrastructure contribute to maintaining the community member's good health in normal times and during a disaster	SDG 3 Indicator 3.8.2 Indicator 3.b.2 Indicator 3.c.1

(*continued*)

Table 1. Analytical framework to assess community resilience

Community resilience indicators	Questions to be answered	Link to SDGs
Secure and sufficient food supply	Does the energy infrastructure contribute to secure and sufficient food supply during disasters?	SDG 2 Indicator 2.1.1 Indicator 2.1.2 Indicator 2.2.2
Hazard-resistant livelihood practices	Does the community use hazard-resistant livelihood practices for food and income security through this energy infrastructure?	SDG 1, Indicator 1.3.1 Indicator 1.5.2 SDG 8 Indicator 8.8.1 Indicator 8.10.1
Measures to strengthen physical capital		
Household asset protection to maintain income flow	Are household asset bases (income, savings and convertible property) sufficiently large, diverse and protected to ensure reduced vulnerability to disaster?	SDG 11 Indicator 11.5.1 Indicator 11.5.2
Local infrastructure: bridges, hospital, clinic, school building, road and water supply system	Are the community's critical infrastructure and basic services resilient to disaster? Does the community have access to health-care facilities and health workers equipped and trained to respond to disasters' physical and mental health consequences, and is it supported by access to emergency health services and medicines, etc.?	SDG 1 Indicator 1.5.2 Indicator 1.5.3 SDG 9 Indicator 9.a.1 SDG 11 Indicator 11.5.2
Housing	Is the community's housing resilient to disaster?	SDG 1 Indicator 1.3.1 Indicator 1.5.1 SDG 11 Indicator 11. b.1
Early warning system;	Is there an operational early warning system in the community to help with contingency and recovery planning?	SDG 4 Indicator 4.4.1 SDG 9 Indicator 9.b.1 Indicator 9.c.1
Emergency shelter	Are emergency shelters (purpose-built or modified) accessible to the community and have adequate facilities to meet all the affected population's basic needs?	SDG 1 Indicator 1.5.2 Indicator 1.5.3 SDG 9 Indicator 9.a.1 SDG 11 Indicator 11.5.1

Source: Authors

Table 1.

direct interview method and stakeholder consultations is the basic evidence of this study. The following sections describe the case studies in detail.

3.1 Case study-1: Distributed generation: solar wind and micro-hydel system providing critical community-owned infrastructure in Thingan, Makwanpur district, Nepal

Makwanpur district is in the Narayani Zone of the Central Development Region of Nepal, consisting of 43 Village Development Committees (VDCs) and one municipality. The case study is focused on Thingan VDC, one of the VDCs of Makwanpur District with a spatial extent of 27°10' to 27°40'N and 84°41' to 85°31'E (Figure 1).

Figure 1.
Makwanpur district in Nepal

Source: Author

3.1.1 Disasters and challenges faced by communities in Thingan (Makwanpur). As per a research report on "experience sharing on climate change among the local people in Makwanpur district" published by DFID, Action Aid and Women and Children Development Forum, local people belonging to this district are facing an increasing risk from natural hazards such as floods, drought and rise in infectious diseases, which have exacerbated human health and economic impacts. The agriculture sector is the highest impacted economic sector, followed by forestry, biodiversity, water-sanitation, health and hydrology and ecology.

Thingan VDC is experiencing frequent loss of productivity in agriculture, waterborne diseases and lack of access to water at the point of consumption. Thereby the time spent on water collection is high. Geographically disadvantaged terrain with a highly dispersed cluster of households providing electricity access through a conventional national grid expansion system is not cost-effective. As a result, households used kerosene and/or candles for illumination service demand. Few individuals or households with small businesses (as an alternative to their agricultural livelihood) in the main Thingan Bazar rely on kerosene or diesel to run their motive power. The local price of diesel and kerosene was relatively high compared to the market price in central city districts like Kathmandu (almost 30% higher, as per the interaction with the shop owners), and the operational cost of running the business went up, leaving smaller profit margin. Lack of electricity in the main market is considered to be the main hindrance to starting alternate livelihood or expanding existing commercial businesses.

As far as the community-level public infrastructure was concerned, there was no streetlight infrastructure, with narrow village roads and houses on the fringe of the forest. There was a police post, health post, small church library and a co-operative house. Primarily due to lack of electricity: the police post, which is supposed to be open at night, but practically stayed closed, and there was no power source for the wireless mobile, etc. The health post had to close in the evening. In 2009–2010, the police and health posts installed individual solar systems to power the basic equipment to meet the demand for illumination, space cooling and extended work hours at night. However, those smaller solar home systems were insufficient to meet a few critical load requirements, such as powering the vaccine refrigerator and other health-related equipment.

3.1.2 Installation of solar wind micro-hydel hybrid system. In 2011–2012, the solar wind-hybrid system and in 2013, also a micro-hydel system was installed in Thingan VDC. The financial resource of the tribrid renewable energy-based power system came from funds raised by expat Nepalese, Nepal Solar Volunteer Corps (NSVC), a team of university professors and engineering students from various universities in South Korea, with a vision to help and support a remote village in rural Nepal to bring light to those in darkness and uplift the basic living standard of the people there.

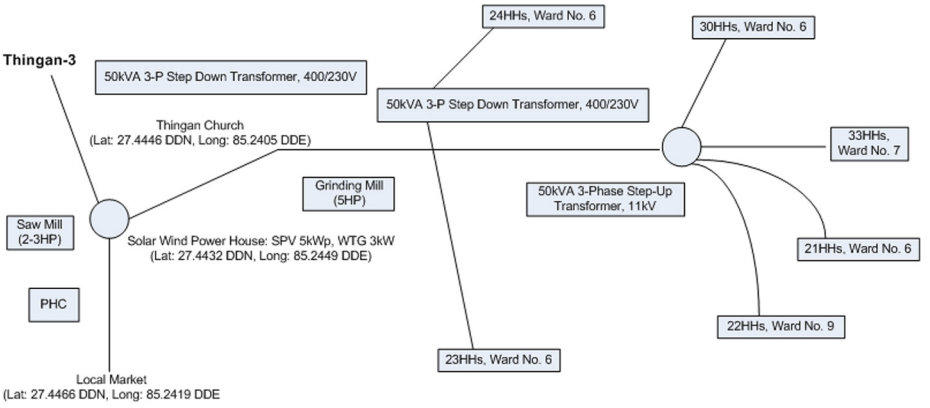
The tribrid system installed at *Thingan VDC of Makwanpur district* consists of:

- 5kW solar PV system;
- 2 kW wind electric generator; and
- 25 kW micro-hydel system.

The 5 kWp solar PV system and wind electric generator were installed in the same location, whereas the micro-hydro site was about 3–4 km from the solar-wind site. The basic sketch below shows the renewable power plants and the loads being provided by those power plants (Figure 2).

A brief description of the tribrid system is given in Table 2.

The five kWp photovoltaic solar system included solar panels, inverters and charge controllers, cables and wiring for transmission lines and homes throughout the village. A small wind turbine with a rated power output of 3.2 kW is installed very close to the location where the solar PV system is installed. The DC electricity generated from the solar PV array and the power generated from the wind are used to charge the battery through the wind-solar charge controller, model: ZY-240 - 8KSW (Figure 3). The battery is then connected to the inverter which converts the DC electricity into single-phase AC electricity distributed within 2 km. Four LED lamps were installed in each home, with each household set to pay a monthly user fee of NRS 150 (US$1.25) flat for up to five units of electricity (kWh) consumption. Hi-tech photo sensor switches were also installed on streetlights to automatically turn them on at dusk and turn them off as the sun shines. The Korean expat Nepalese team technically designed and funded the project, while villagers, with their labour, constructed a building to house the batteries that will store the energy harnessed from solar PV. A User's Committee was also



Source: Author

Figure 2.
Basic schematic of the distribution of power from this tri-hybrid system to different clusters of households

Item	Description
Total system capacity (in kW)	*28 kW*
Type of energy generating unit (wind/solar/DG/micro-hydro/others)	*Wind, solar and micro-hydel*
Available RE resources capacity (in kW)	Solar *5 kW* Wind *3 kW* Micro-hydro *20 kW* Others, if any *NA*
Daily load profile, if available	*Not available*
Battery bank	*4800 Ah, 96V battery bank used in the wind + solar powerhouse*
Type of distribution network (whether one-phase or three-phase) and length also with voltage rating (11 kV, 400 V, 220 V)	*Transmission lines three phase, 11 kV* *Distribution lines one phase, 220 V*
System voltage level for the solar hybrid system	*220 V*
Whether the existing systems are grid-tied/off-grid	*Off-grid*
Metering arrangements (any energy metre used at the household level or another place)	HHs using energy metre *250* HHs using MCB/cut-out fuse *250*

Source: Field visit by lead authors

Table 2.
Brief technical details of the tribrid system

Source: Author

Figure 3.
Solar PV, wind electric generator and battery bank installed at the site

formed at the village level soon after the commissioning of the power system for its regular operation and maintenance of the system. The tariff collected from the end-users is used towards the operation and maintenance of the system.

The new tribrid system has provided electricity to Ward No. 3, 6, 7 and 9 of Thingan VDC, comprising of 250 households. The system gained legitimacy as it got legalized according to the law of the land and is registered in the Chief District Officer's office in Hetauda, Makwanpur, under the name of Miteri Power Plant.

All the components of the MHP plant were in good working condition after one and a half years of installation. About 7 km of transmission lines and more than 10 km of distribution lines have been used. A 24 kW ballast tank is also used to dump any excess power produced (Figure 4).

3.1.3 Scale of the service area for the solar-wind-micro-hydro tribrid system. Almost all the households[1] in these four wards of Thingan VDC, shops in the markets and grinding mills were electrified, which ensured extended hours of productive work and increased income for the shop owners. Every house in the village was provided with Four LED bulbs, each of 7.2 W (made in South Korea and provided by NSVC) and also with a power socket for

Source: Author

Figure 4.
Snapshots of the existing micro-hydropower generating site

charging mobile phones and for using other low power-consuming devices like laptops, TV, radio, fans, etc., the community were able to get latest information regarding various aspects of health, agriculture, entertainment through the mobile.

Health post also started using a refrigerator 24 h per day to make ice to preserve some medicines and vaccines. The library started using computers and LED projectors, as needed, to access the latest information services. The office of the co-operative in the village started using a desktop computer as they are engaged in managing operations and information on the upliftment of the lower-income category people in rural and peri-urban areas through various government schemes. Two tailor shops could use electric iron, and 17 streetlights were installed in Ward No. 3 of the VDC. Local villagers use the rooms attached to the solar and wind powerhouse as poultry farms.

3.1.4 Institutional mechanism and power tariff structure. Institutionally, the User's Committee is responsible for the long-term sustenance of the system and governs other small committees formed in each cluster of houses. These small committees collect tariffs each month and submit them to the main User's Committee. A minimum fixed amount of US$2 per 5 kWh is charged for residential, commercial and community entities (Figure 5).

The situation of the Thingan VDC before and after the installation of the tribrid is summarized in Table 3.

3.2 Case study-2: Solar PV powered rural health centres in rural India

3.2.1 Disasters and challenges faced by communities. In India, the National Rural Health Mission aims to provide the rural population with equitable, affordable and quality health care. Rural India is home to about 889 million (The World Bank, April 2019) primarily dependent on the rural health-care system. India has approximately 29,000 PHCs and 5,500 Community Health Centres. These services are administered via community-owned, decentralized health-care systems, which play an important role in births, immunization, antenatal and neonatal care. The absence of a reliable and quality electric supply system

Figure 5.
Snapshots of shops and health posts using the electricity from the tribrid system

Source: Author

adversely impacts the overall service delivery of the health centres even if the medical equipment and staff are available adequately to prevent and manage any health-related disasters.

This case study considers the solarization of the health centre programme of the Chhattisgarh Renewable Energy Development Agency, a state renewable energy development agency in India, in collaboration with the state health mission. In Chhattisgarh, 900 rural health centres have been installed with off-grid solar PV with a cumulative capacity of 3 MW across the state. The case study has compiled and analysed the improvement of the health-care system by installation of the solar PV system.

3.2.2 Technology and finance. Most of the solar PV systems installed at each PHC site in Chhattisgarh have 2 kW capacity with 48V, 200 Ah battery bank, which can provide a backup of 3–4 h daily to a well-equipped PHC. With the average duration of daily power cut of 2–3 h in most places in the state, these PV systems with battery backup, can provide an uninterrupted, reliable power supply for 24 h to the PHCs.

The original design of the system envisaged the inclusion of illumination and space cooling service through fans in the OPD room, the labour room and the cold chain room and also the connection of the freezer and the ice-lined refrigerator (ILR) to ensure that the cold chain equipment.

As per the field experience, there are PHCs connected to the state power grid with a supply of electricity for more than 85% of the time in a day (locally, they are identified as power non-deficit PHCs). PHCs connected to the state power grid but not with guaranteed continuous supply and thus have unmet power demand (i.e. power deficit PHCs). In total, 26% of the power deficit PHCs have solar PV systems as backup used during power cuts, while around 10% of such PHCs have no solar backup systems.

PHCs that reported severe adverse impact, especially for in-patient and delivery services due to lack of electricity, were significantly higher in number from among the power-deficit PHCs (Figure 6).

Village clusters catered	Before installation	After installation
District Zone	Makwanpur Narayani	
Access to quality electricity supply	None	Residential 234 HH Commercial 12 Community entities police post 1 Health post 1 Church 1 School 1 Others street lights 17 nos. Total: 250
Type of energy services provided	Nil	• *For residential sectors*: four light points and one plug point for charging mobile per household *For community entities*: • A refrigerator in health post for throughout the day • Library used a laptop and an LED projector as needed • Co-operative office in the village used a desktop computer as needed • 17 streetlights have been installed *For commercial entities (shops)*: • Two additional tailor shop • Poultry farm
Addressing climate change by		Clean energy installations through the replacement of fossil fuel-based generating systems.

Source: field survey

Table 3.
Situation of the Thingan VDC before and after the installation of the tri-hybrid system

In total, 27.6% of PHCs with solar power backup (against 8.6% without solar) can keep and successfully run the cold chain equipment, that is, deep freezer and ILR, to provide better health services (Figure 7).

PHCs are the critical infrastructure in the villages. Most of the PHCs with solar power backup confirmed 85%–95% of OPD services, in-patient services and delivery services, which is around 50% higher than the ones with no solar power backup systems. In total, 52% of PHCs reported laboratory services were possible due to solar power systems besides powering lights, fans and cold chain equipment in the laboratory. PHC health services improved by around 50% as the installation of solar systems reduced the impact of power cuts. Some PHCs also reported having reduced incidences of equipment damage due to voltage fluctuation. Demand from PHCs increased at least by 25%–40% more to bear a greater load and thereby reduce their dependence on the grid. About 37% of the sample PHCs reported that their water supply was adversely affected due to a lack of electricity supply, adversely impacting child delivery and the prevention and control of infections. Significant opportunities exist to simultaneously address the (often competing) goals of energy access, energy security, resource management and health outcomes (Table 4). Solar for health is one such example of a success story in Chhattisgarh.

Conclusion

Community resilience building in the provisioning of on-demand electricity service through granular technology and distributed generation is successfully emerging in Nepal and India with scope for scale-up. However, many synergistic actions that need to happen simultaneously to make this systemic change happen and get socially embedded. A case study of Nepal on a distributed generation system innovation using a solar-wind-micro-hydro system in 2013 and a case study of India on widespread solarization provide insights for the scale up of community resilience building through renewable energy. Supply systems in the case study area have addressed the local community level existing unmet demand for modern energy access for productive use.

The case studies help us identify how, following the demand, a successful community scale commercially viable distributed power generation model can be set up to address a basic driver of vulnerability arising out of lack of access to reliable power supply. It is evident from the case study of Nepal that modern electricity is playing an important role in livelihood diversification at the community level. The community also participated in the technology installation and innovation targeted for the community benefit. Technology innovation through the onsite development of the tribrid system in a difficult terrain within a stipulated period created social innovation through trust and human capacity building within the community. However, little exposure of the operator and the community to the technical aspects of the tribrid and its

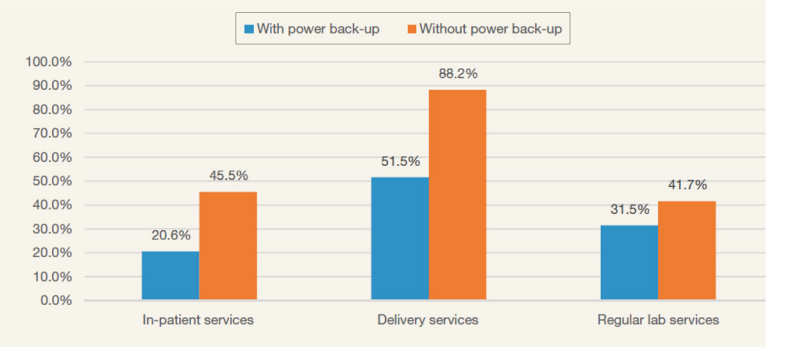


Figure 6.
Comparison of various service levels in PHCs with and without power backup

Source: CEEW Analysis, 2017

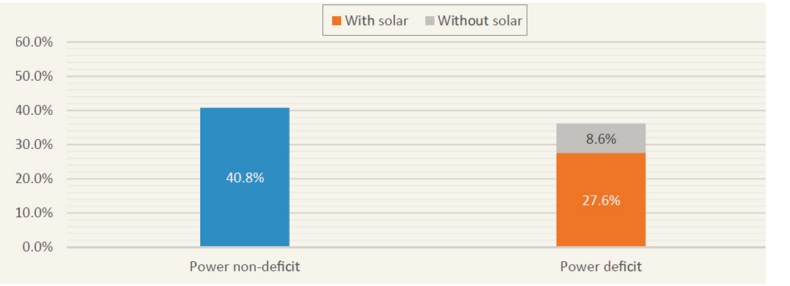


Figure 7.
PHCs with solar power backup

Source: CEEW Analysis, 2017

Community resilience measures	Questions	Case study-1	Case study-2
Participatory risk assessment Scientific risk assessment	Does the community combine local knowledge and risk perception with scientific knowledge, data and assessment methods?	Yes, the participation of local people with the expatriate scientific team helped in the process and contextualization.	The scope was less as it was more of a ready-to-install technology, but community feedback helped
Education of children on DRR; rights, awareness and advocacy	Have community members been exposed to/have participated in DRR specific awareness events (campaigns, discussions and training) and have improved awareness and practices as a result?	Once the electricity and internet services were available in the village, the community group organized educational and entertainment sessions. Sessions touched upon climate change-related disasters and risks. How far children were involved was not known	Not applicable
Community decision-making; inclusion of vulnerable groups; participation of women	Is the community leadership committed, effective and accountable? Are the vulnerable groups in the community included and represented in community decision-making?	The Village Energy Committee included members from each household, including participation from women. The energy infrastructure brought the community together with a common purpose.	Not applicable as this is not a community-based model
Sustainable environmental management; water security management	Does the community have access to sufficient water quantity and quality for domestic needs during disasters?	Environmental management practices such as using efficient lights, lesser or no use of kerosene or diesel for irrigation purposes, regular cleaning of the stream and availability of water taps for clean drinking water, had been introduced with the hybrid RE system. Drinking water systems linked to the RE system provided water even during heavy rain/drought	Access to regular electricity also enables access to a regular water supply for many PHCs

(*continued*)

Table 4.
Community resilience measures and energy access, energy security, resource management and health outcomes

Table 4.

Community resilience measures	Questions	Case study-1	Case study-2
Health access and awareness	Does the energy infrastructure contribute to maintaining the community member's good health in normal times and during a disaster?	An uninterrupted power supply to the health clinics from the RE system has substantially increased the possibilities of good health of community members even during a disaster	Services such as cold chain, in-patient care and deliveries were seen to be less impacted due to the lack of grid supply after installing the solar system
Secure and sufficient food supply	Does the energy infrastructure contribute to secure and sufficient food supply during disasters?	Not enough evidence is available. However, the RE infrastructure can also be used to power irrigation systems, cold storage and other food supply systems in the value chain to ensure continuous food supply even during climate shocks and disasters	
Hazard-resistant livelihood practices	Does the community use hazard-resistant livelihood practices for food and income security through this energy infrastructure?	The RE intervention has created a number of livelihood options that were previously unavailable due to a lack of electricity supply	Health officials worked extended hours, which allowed the doctors to serve more outpatients
Access to market	Has the local market grown with energy services and linked products, labour and services protected against shocks?	New businesses came up for extended hours, such as grocery, medicine, cycle repair, flour mills and snack bars	–
Access to financial services	Whether formal or informal, are there affordable and flexible financial services (savings and credit schemes, microfinance)?	Microfinancing institutions had come forward to provide credit schemes for starting new businesses as their confidence level regarding the repayment of the loan increased	Not applicable
Income and asset protection	Are household asset bases (income, savings and convertible property) sufficiently large and diverse and protected to ensure reduced vulnerability to disaster?	No concrete evidence is available.	
	Does the community have access to informal and formal	No concrete evidence is available	

(*continued*)

Community resilience measures	Questions	Case study-1	Case study-2
Social protection; social cohesion and conflict prevention	social protection schemes that support disaster risk reduction and recovery? Is there a sense of peace, security and effective conflict prevention and mitigation mechanisms, both within the community and with other communities?		
Critical infrastructure		Are the community's critical infrastructure and basic services resilient to disaster?	Some of the critical infrastructures, such as health centres, police posts and drinking water facilities, became more resilient due to the supply of reliable electricity and better maintenance of these infrastructures
The solar PV system has made the health infrastructure/PHC more resilient with uninterrupted backup power		Due to the electricity supply from the RE system to the households or PHCs, resilience has increased; however, there is no evidence if the housing is resilient to all kinds of disasters.	
Housing	Is the community's housing resilient to disaster?	–	–
Contingency and recovery planning	–	–	–

(*continued*)

Table 4.

Table 4.

Community resilience measures	Questions	Case study-1	Case study-2
Early warning system	Is there an operational early warning system in the community	No	No
Capacity in preparedness, response and early recovery	–	–	–
Services in emergencies (health, education services)	Does the community have access to health-care facilities and health workers equipped and trained to respond to physical and mental health consequences of disasters supported by access to emergency health services, medicines, etc.?	The community has much better access to the health-care facility and educational facilities due to the reliable supply of power from the RE system, with health workers staying longer hours, access to medicines and vaccines in the health post and PHCs improved	
Emergency infrastructure	Are emergency shelters (purpose-built or modified) accessible to the community and have adequate facilities to meet all the affected population's basic needs?	–	–
Leadership and volunteerism in response and recovery	Does the community play a leading role in co-ordinating preparedness, response and recovery, reaching all affected people – including the most vulnerable – through organized and trained volunteers?	Enhanced community scale activity is a positive trend in this direction	PHCs became institutional support

Source: field survey

associated system (such as safety measures applicable for regions with high altitude and barren land and with the possibility of heavy lightening) may make the infrastructure and services more vulnerable and thus need handholding in the technical and managerial aspect of the tribrid system. State and national governments can play a critical role in rolling out handholding programmes for such interventions to ensure long-term sustainability.

While state-of-the-art technologies can be promoted to achieve better efficiency and reliability of the system, it should plan for the basic and customised training for initial handholding of the local community and dedicated operators. While the Nepal case study explores the enabling factors through the community financing mechanism, the India case study shows enhanced health services through the installation of solar PV systems. However, to scale up such interventions, a better business model can be developed to implement the public-private partnership principle effectively. Public funds can be created and used to identify the appropriate sites and cluster to ensure quality assurance, monitoring and evaluation of the system along with training handholding and awareness campaign; private sector involvement should be in the installation and operation of such system with a fee for service basis or through other revenue model, mutually agreed by all the stakeholders involved.

Recommendations

To build community scale resilience, provision of access to uninterrupted electricity service to community members is a primary necessity. However, without the public sector's active role, only private investment cannot guarantee sustainability. The public sector needs to identify and create a database of sites where distributed generation systems with a diverse mix of local renewable sources need to be set up in the public domain. Public sector investment in awareness building and training of local community members is a primary requisite for private investors to step in with community participation.

Note

1. Few households which are far from the transmission and distribution lines are still not connected and lack access to supply system and are using solar home systems for meeting partially their very minimum basic energy service requirements.

References

Aditya Ramji, A., Sasmita Patnaik, S., Sunil Mani, S., Hem, H. and Dholakia, H.H. (2017), "Powering primary healthcare through solar in India", *Lessons from Chhattisgarh*, CEEW Report and Oxfam India.

Chakravarty, D. and Joyashree Roy, J. (2021), "Solar microgrids in rural India: a case study of household benefits", *Ecology, Economy and Society–the INSEE Journal*, Vol. 4 No. 2, pp. 65-93, available at: https://ecoinsee.org/journal/ojs/index.php/ees/article/view/140

Firstpost (2021), available at: www.firstpost.com/world/at-sindhs-primary-healthcare-centres-solar-power-is-helping-save-the-lives-of-mothers-9396071.html

Hanley, N., Shogren, J.F. and White, B. (1997), *Environmental Economics in Theory and Practice*, Macmillan, Bristol.

Hasselqvist, H., Renström, S., Strömberg, H. and Håkansson, M. (2022), "Household energy resilience: shifting perspectives to reveal opportunities for renewable energy futures in affluent contexts", *Energy Research and Social Science*, Vol. 88, doi: 10.1016/j.erss.2022.102498.

Hishan, S.S., Ramakrishnan, S., Mansor, N.N.B., Rahim, A.R., Chuan, L.T., Mahmood, A. and Beri, N. (2021), "Understanding disaster risk and development of resilience as one of the fundamental

drivers of sustainable development in India with special reference to super cyclone Amphan", *International Journal of Disaster Risk Reduction*, Vol. 62, doi: 10.1016/j.ijdrr.2021.102339.

IPCC (2018), "Summary for policymakers. In: global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty", in Masson-Delmotte, V.P., Zhai, H.-O., Pörtner, D., Roberts, J., Skea, P.R., Shukla, A., Pirani, W., Moufouma-Okia, C., Péan, R., Pidcock, S., Connors, J.B.R., Matthews, Y., Chen, X., Zhou, M.I., Gomis, E., Lonnoy, T., Maycock, M., Tignor. and Waterfield, T. (Eds), *World Meteorological Organization*, Geneva, Switzerland, p. 32.

Lwin, K.K., Pal, I., Shrestha, S. and Warnitchai, P. (2020), "Assessing social resilience for flood-vulnerable communities in Ayeyarwady Delta, Myanmar", *International Journal of Disaster Risk Reduction*, Vol. 51, p. 101745, doi: 10.1016/j.ijdrr.2020.101745.

Marshall, N.A. and Marshall, P.A. (2007), "Conceptualizing and operationalizing social resilience within commercial fisheries in Northern Australia", *Ecology and Society*, Vol. 12 No. 1, doi: 10.5751/ES-01940-120101.

Mehelin, N. (2020), *Cox's Bazar: 40 Cyclone Shelters Offer Protection for 40,000 People*, WorldFood Program, Bangladesh.

Mohanty, A., Hussain, M., Mishra, M., Kattel, D.B. and Pal, I. (2019), "Exploring community resilience and early warning solution for flash floods, debris flow and landslides in conflict prone villages of Badakhshan", *International Journal of Disaster Risk Reduction*, Vol. 33.

Mongabay (2021), "Rooftop solar prepares prosumers in Odisha for power cuts during disasters", available at: https://india.mongabay.com/2021/11/solar-energy-prepares-prosumers-in-odisha-for-power-cuts-during-disasters/ (last updated in Nov 2021).

Obrist, B., Pfeiffer, C. and Henley, R. (2010), "Multi-layered social resilience: a new approach in mitigation research", *Progress in Development Studies*, Vol. 10 No. 4, pp. 2010-2293, doi: 10.1177/146499340901000402.

Pal, I. and Bhatia, S. (2017), "Disaster risk governance and city resilience in Asia-pacific region", *Science and Technology in Disaster Risk Reduction in Asia: Potentials and Challenges*, pp. 137-159, doi: 10.1016/B978-0-12-812711-7.00009-2.

Pal, I., Ghosh, T. and Ghosh, C. (2017), "Institutional framework and administrative systems for effective disaster risk governance – perspectives of 2013 cyclone phailin in India", *International Journal of Disaster Risk Reduction*, Vol. 21

Patel, S., Rogers, M., Amlˆot, R. and Rubin, G. (2017), "What do we mean by 'community resilience'? A systematic literature review of how it is defined in the literature", *PloS Curr. Disasters*, Vol. 9.

Peerapong, P. and Limmeechokchai, B. (2017), "Optimal electricity development by increasing solar resources in diesel-based micro grid of island society in Thailand", *Energy Reports*, Vol. 3, pp. 1-13, doi: 10.1016/j.egyr.2016.11.001.

Rao, N.D., Min, J. and Mastrucci, A. (2019), "Energy requirements for decent living in India, Brazil and South Africa", *Nature Energy*, Vol. 4 No. 12, pp. 1025-1032, doi: 10.1038/s41560-019-0497-9.

Roy, J., Islam, S.T., Pal, I. and Mahmud, H. (2021a), "A white paper on: top ten priorities: in implementation of low carbon sustainable energy development and adaption framework to reduce disaster impact in the context of Bangladesh, Bangabandhu chair special issue, energy, disaster, climate change: sustainability and just transitions in Bangladesh", *International Energy Journal*, Vol. 21 No. 1A, pp. 143-145.

Roy, J., Islam, S.T. and Pal, I. (2021b), "Implementation framework for sustainable development: what matters in the context of Bangladesh, bangabandhu chair special issue, energy, disaster, climate change: Sustainability and just transitions in Bangladesh", *International Energy Journal*, Vol. 21, pp. 1-8.

Sharifi, A. (2016), "A critical review of selected tools for assessing community resilience", *Ecological Indicators*, Vol. 69, doi: 10.1016/j.ecolind.2016.05.023.

Sharifi, A. and Yamagata, Y. (2016), "On the suitability of assessment tools for guiding communities towards disaster resilience", *International Journal of Disaster Risk Reduction*, Vol. 18 No. 2016, doi: 10.1016/j.ijdrr.2016.06.006.

Sharma, K.R., Palit, D., Mohanty, P. and Gujar, M. (2014), "Approach for designing solar photovoltaic-based mini-grid projects: a case study from India", in Bhattacharyya, S. and Palit, D. (Eds), *Mini-Grids for Rural Electrification of Developing Countries. Green Energy and Technology*, Springer, pp. 167-201, doi: 10.1007/978-3-319-04816-1_8.

Sothea, K. and Oanh, N.T. (2019), "Characterization of emissions from diesel backup generators in Cambodia", *Atmospheric Pollution Research*, Vol. 10 No. 2, pp. 345-354, doi: 10.1016/j.apr.2018.09.001.

United Nations (2015), "Transforming our world: the 2030 agenda for sustainable development", available at: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf

Further reading

Clark-Ginsberg, A.B., McCaul, B., Bremaud, I., Cáceres, G., Mpanje, D., Patel, S. and Patel, R. (2020), "Practitioner approaches to measuring community resilience: the analysis of the resilience of communities to disasters toolkit", *International Journal of Disaster Risk Reduction*, Vol. 50, doi: 10.1016/j.ijdrr.2020.101714.

Gibson, M.J., Chen, A.S., Khoury, M., Vamvakeridou-Lyroudia, L.S., Stewart, D., Wood, M. and Djordjević, S. (2020), "Case study of the cascading effects on critical infrastructure in torbay coastal/pluvial flooding with climate change and 3D visualisation", *Journal of Hydroinformatics*, Vol. 22 No. 1, pp. 77-92.

Gujar, M., Datta, A. and Mohanty, P. (2013), "Smart mini grid: an innovative distributed generation based energy system", 2013 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia), pp. 1-5, doi: 10.1109/ISGT-Asia.2013.6698768.

Medium.com (2024), available at: https://medium.com/world-food-programme-insight/combatting-natural-disasters-with-cyclone-shelters-d711e27d2fa8

Rao, N.D. and Min, J. (2017), "Decent living standards: Material prerequisites for human wellbeing", *Social Indicators Research*, Vol. 138 No. 1, pp. 225-244, doi: 10.1007/S11205-017-1650-0.

Thanvisitthpon, N., Shrestha, S. and Pal, I. (2018), "Urban flooding and climate change: a case study of bangkok", *Environment and Urbanization ASIA*, Vol. 9 No. 1.

Thanvisitthpon, N., Shrestha, S., Pal, I., Ninsawat, S. and Chaowiwat, W. (2020), "Assessment of flood adaptive capacity of urban areas in Thailand", *Environmental Impact Assessment Review*, Vol. 81.

Corresponding author

Indrajit Pal can be contacted at: indrajit-pal@ait.ac.th

For instructions on how to order reprints of this article, please visit our website:
www.emeraldgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: **permissions@emeraldinsight.com**

ENVIRONMENTAL RESEARCH
LETTERS

EDITORIAL • OPEN ACCESS

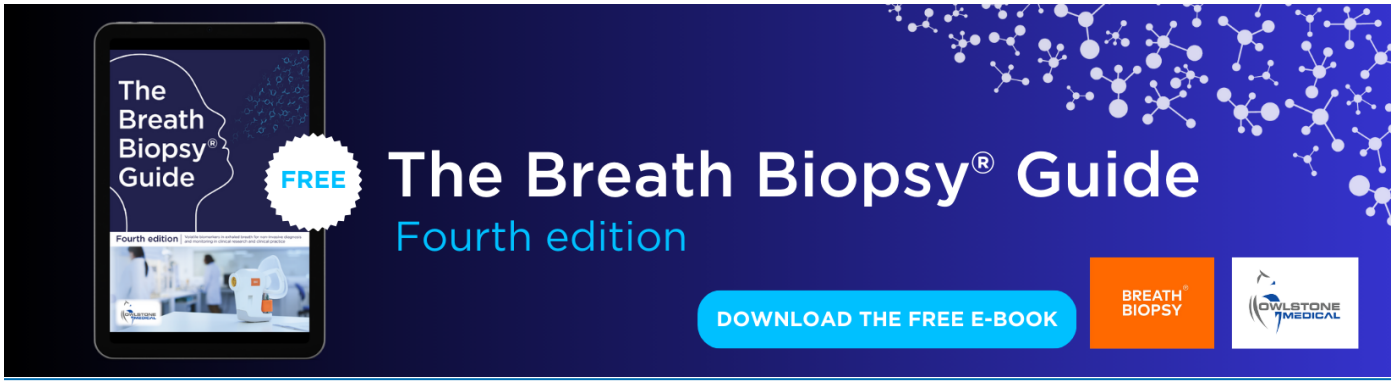
Demand-side climate change mitigation: where do we stand and where do we go?

To cite this article: Felix Creutzig *et al* 2024 *Environ. Res. Lett.* **19** 040201

View the article online for updates and enhancements.

You may also like

- Climate change mitigation in cities: a systematic scoping of case studies
Mahendra Sethi, William Lamb, Jan Minx et al.
- Reviewing the scope and thematic focus of 100 000 publications on energy consumption, services and social aspects of climate change: a big data approach to demand-side mitigation
Felix Creutzig, Max Callaghan, Anjali Ramakrishnan et al.
- Coal transitions—part 1: a systematic map and review of case study learnings from regional, national, and local coal phase-out experiences
Francesca Diluiso, Paula Walk, Niccolò Manych et al.



This content was downloaded from IP address 203.159.58.113 on 27/03/2024 at 07:06

IOP Publishing Environ. Res. Lett. 19 (2024) 040201 https://doi.org/10.1088/1748-9326/ad33d3

ENVIRONMENTAL RESEARCH
LETTERS

EDITORIAL

Demand-side climate change mitigation: where do we stand and where do we go?

Felix Creutzig[1,2,*], Joyashree Roy[3] and Jan Minx[1,4]

[1] Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany
[2] Sustainability Economics of Human Settlements, Technische Universität Berlin, Berlin, Germany
[3] Asian Institute of Technology, Bangkok, Thailand
[4] Priestley Centre for Climate Futures, School of Earth and Environment, University of Leeds, Leeds, United Kingdom
[*] Author to whom any correspondence should be addressed.

E-mail: creutzig@mcc-berlin.net

OPEN ACCESS

RECEIVED
22 February 2024

ACCEPTED FOR PUBLICATION
14 March 2024

PUBLISHED
22 March 2024

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Abstract

It is now well established that the demand side can contribute substantially to climate change mitigation thus increasing the solution space. The recent IPCC synthesis report for the first time explicitly reflected this class of solutions. Here, we provide an overview of an unique set of 22 review papers published in the focus issue of Environmental Research Letters. We also extract a key set of insights, ranging from the varied but rapidly evolving literature to demand-side mitigation potential, relevance for well-being, and consistent categorization of options across end-use sectors. We find that demand-side approaches to climate change mitigation supplement exclusively technology-focused supply side solutions and, in many cases, comprise system-wide effect contributing to well-being and planetary stability. Review studies cover macro-economics, well-being, and sustainable development goals on the metric side, and investigate consumption-based individual options, urban strategies, transport, building, and food sector potentials, but also the role of the circular economy, material efficiency, and digitalization. Demand-side measures can be categorized into avoid, shift, and improve approaches. Several additional reviews systematically investigate psychological and social approaches and initiatives to foster climate change mitigation. We finally outline important gaps and questions to be tackled in the coming years.

In this editorial, we synthesize a special issue and the findings from 22 systematic reviews on climate change mitigation that identify and scrutinize demand-side solutions for climate change mitigation. These reviews provide a comprehensive overview of the current state of research in this vital area, helping to shape and substantiate the most recent IPCC report (Skea *et al* 2022, Creutzig *et al* 2022b). Demand-side climate change mitigation is increasingly recognized as essential for achieving ambitious climate targets, supplementing supply side solutions firmly embedded in climate stabilization scenarios. This collection of reviews is particularly timely, given the pressing need to address these targets, but also considering the potential benefits of demand-side solutions for society. These solutions not only help in reducing greenhouse gas (GHG) emissions but also offer services that increase well-being and are consistent with broader planetary stability goals, such as reduced land use.

The demand-side of climate change has always been implicit in economic and social science research on climate change mitigation, but until recently has not been explicitly covered and quantified in assessment on climate solutions. A review synthesized how the 5th IPCC assessment report provided cases and examples on demand-side climate change mitigation in various chapters (Creutzig *et al* 2016). In a community wide effort, an outline of the scope of demand-side climate change mitigation was explored, highlighting the categorization of demand-side measures into avoid, shift, and improve (ASI) approaches (Creutzig *et al* 2018). We will see that this simple ASI categorization recurrently appears in this focus issue.

In this editorial, we discuss the review papers in 5 clusters. First, we start with an overview of

© 2024 The Author(s). Published by IOP Publishing Ltd

the literature base. It begins with a discussion on 'History and Narratives', providing context and background on the evolution of demand-side mitigation. This is followed by an exploration of the 'Political Economy', assessing the influence of various stakeholders and economic factors. The next section, 'Economics of Transitioning', delves into the financial and economic implications of adopting demand-side strategies. Additionally, the 'Geography' section aims to address regional disparities and the unique challenges faced by different areas in implementing these strategies. Through these clusters, the editorial aims to provide a comprehensive understanding of demand-side climate change mitigation, setting the stage for the detailed reviews that follow.

1. The literature on demand-side solution evolves rapidly, and even more so than the climate change solution literature in general

A thorough analysis of the literature of demand side of climate change mitigation first requires a map of the literature and an accompanying definition of which part of the literature does so. The review titled 'Reviewing the scope and thematic focus of 100 000 publications on energy consumption, services and social aspects of climate change: a big data approach to demand-side mitigation' (Creutzig *et al* 2021) does so and presents a comprehensive review of literature on energy consumption, services, and social aspects of climate change. The review is based on a big literature data approach and focuses on demand-side mitigation.

The authors used a two-pronged approach to gather data. First, they used a top-down search query that yielded around 30 000 results. They then asked domain experts to identify five of the most important papers in their specific field relevant to demand, services, and social aspects of mitigation. Interestingly, over 50% of these papers were not discovered by the top-down query.

To address this, the authors developed 27 search queries that investigated aspects of the issue list in much more detail. These queries found 63 847 documents, of which 34% (21 913 documents) were also identified by the top–down search query. This means that expert queries identified two-thirds of documents not yet obtained by the top-down query, highlighting the important role of domain-experts in deriving search queries. The overall growth of the literature outperforms the overall literature on climate change solutions.

The authors then used topic modeling, an unsupervised machine learning technique, to explore the content of the studies in their queries, identifying four key clusters: policy, housing, mobility, and food/consumption. The mobility literature, specifically, sheds light on the significant role of transport in climate change mitigation, emphasizing the need for shifts in transport modalities and improved urban infrastructure to reduce dependency on personal vehicles. This insight is crucial in understanding how changes in mobility patterns can significantly contribute to reducing GHG emissions and enhancing urban sustainability. The housing literature emphasizes investments and refurbishment by homeowners, but also social and collective action, while the food/consumption literature points to the importance of behavioral change and its dynamic interaction with social norms. These clusters suggest that demand-side solutions can significantly improve public health. The centrality of the policy cluster within these findings underscores the critical role of political actions in integrating and enhancing the effectiveness of various demand-side approaches. This comprehensive analysis maps the underlying epistemic communities, demonstrating the interconnectedness of these areas of study in the broader context of demand-side climate change mitigation.

The study concludes that while the generic search of the 'chapter' queries is good at identifying the overall topics, expert domain queries find a high amount of additional literature (41 934 documents), making expert search queries and knowledge important for identifying in-depth literature.

A complementary, 'Systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping' (Wiedenhofer *et al* 2020) investigates the literature on how macro-economic metrics relate to climate change mitigation. The systematic map and review scrutinizes the empirical literature on decoupling, focusing on the observed relationships between economic growth (approximated as GDP growth), resource use decoupling (materials, energy), and impact decoupling for GHG emissions on the national to global scale. The authors aim to understand the development of the relevant research streams, their conceptual and methodological approaches, and limitation, identifying three focal areas: energy flows and energy conversion chains in socio-economic systems, a more comprehensive perspective asserting that materials and energy are necessarily interlinked, and a stream based on data obtained from material and energy flow analysis. The authors find that decomposition and regression analyses (28%) and econometric time-series analyses (24%) are the most prevalent methods used in the studies. They also find that 46% of the analyses are single-country analyses, with China leading with 157 analyses, followed by the USA with 31 analyses.

The results implicate that future work should focus on comprehensive multi-indicator long-term analyses, conceptually grounded on the fundamental biophysical basis of socio-economic activities, incorporating the role of global supply chains as well as the wider societal role and preconditions of economic growth. The authors also suggest that understanding the interdependencies between economic growth and resource use and/or emissions is crucial, an area where demand-side measures play an important role.

2. Demand-side mitigation is an essential and relevant strategy to achieve climate goals especially in the mid-term until 2050

What is the overall scope and potential of demand-side solutions for climate change mitigations? In a review study in Nature Climate Change, aligning and quantitatively synthesizing the findings of this focus issue, Felix Creutzig *et al* comprehensively assess demand-side mitigation strategies for climate change and their impacts on well-being (2022a). The study categorizes these strategies into ASI options across various end-use sectors and identifies their aggregate mitigation potentials. The findings indicate that demand-side options can reduce sectoral emissions by 40%–70% until 2050, with largely beneficial effects on well-being: 79% of these impacts are positive, 18% neutral, and only 3% negative, emphasizing that such strategies not only aid in climate mitigation but also enhance various aspects of human well-being.

A systematic review of macro-economic factors, such as GDP, and their effect on GHG emissions substantiates the relevance of demand-side measures for achieving the goals of the Paris agreement. Specifically, 'A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights' provides a comprehensive review of the relationship between economic growth and various resource-use and emission indicators (Haberl *et al* 2020).

The authors conducted a qualitative synthesis of strategies and policy recommendations by drawing a random subsample of 15% from 835 articles, yielding 125 articles for further qualitative content synthesis. They used definitions of green growth and degrowth to interpretatively map the 125 papers. Articles were classified as 'green growth' if their framing aimed at absolute or relative decoupling without impeding economic growth. Articles were classified as 'degrowth' if their framing explicitly challenged the primacy of economic growth over the (absolute) reduction of resource use and emissions. Papers not meeting these criteria were classified as 'others'.

The review reveals that most observed decoupling is relative (less GHG emissions per unit of GDP) but not absolute (reduced GHG emissions). However, several countries display absolute decoupling, including a reduction in consumption based emissions (Quéré *et al* 2019, Lamb *et al* 2021). While there can be optimism on accelerating decarbonization in the energy sector due to low cost renewables (Creutzig *et al* 2023), Haberl *et al* rightly emphasize that demand-side measures, focused on improving well-being, while keeping energy use and GHG emissions low, are key to maintain the feasibility of keeping temperatures below 2 °C. Another review in this focus issue (see also below) proposes that the development of well-being approaches of mitigation pathways should be a new research direction (Saujot *et al* 2020). They suggest that the concept of lifestyle is a pivotal notion for such research, which will contribute to improving the assessment of pathways in terms of desirability, and thus feasibility.

In this light, Haberl *et al* also argue that GDP may be becoming an increasingly irrelevant measure of welfare, as it was only loosely coupled with well-being in OECD countries over the last 40 years. They suggest that GDP should be replaced or at least complemented by measures of wellbeing and planetary health. The question of how a good life for all on the planet can be organized within the planet's environmental limits may be more important than the extent to which GDP can be decoupled from resource use or emissions.

Demand-side measures are not only effective but also align well with sustainable development goals (SDGs) and the corresponding well-being dimensions, a key insights of the review 'Demand side climate change mitigation actions and SDGs: literature review with systematic evidence search' (Roy *et al* 2021) (see also (Creutzig *et al* 2022a) for a comprehensive well-being assessment). Similar to Ivanova *et al,* Roy *et al* categorize various demand side actions into the ASI categories. The 'Avoid' category includes actions aimed at avoiding the demand for high-emission intensive services; actions in the 'Shift' category help in substituting demand for high-emission intensive services with low/no intensive ones; and 'Improve' category actions are aimed at improving the energy/emission intensity of a service type.

The review finds that most of these demand side mitigation actions showed positive linkages with SDGs 7 (Affordable and Clean Energy), 9 (Industry, Innovation, and Infrastructure), and 11 (Sustainable Cities and Communities), highlighting the importance of looking at the longer term in a sustainability context, such as the performance of green buildings and the rebound effect of energy efficiency. Demand side actions to be effective enough need a systemwide embedding. For optimizing the mitigation actions, the interconnectedness across sectors is important. For example, demand side mitigation actions in the transport sector are highly dependent

on city planning and infrastructure, as also emphasized in novel technical estimates (Nachtigall *et al* 2023), and the construction sector is an integral part of the building sector.

For the relevance of demand-side measures, Roy *et al* suggest that a better understanding of the costs and benefits of these solutions could facilitate higher adoption. High upfront costs of low carbon options, inadequate infrastructure, incorrect understanding or low awareness regarding sustainable options, and socio-cultural factors currently limit uptake.

However, there are also trade-offs, for example at the interface between adaptation and energy demand. The study 'When adaptation increases energy demand: a systematic map of the literature' provides a comprehensive review of the literature on the impact of adaptation measures on energy demand (Viguié *et al* 2021), also investigating adaptation actions that moderate energy demand.

The number and type of actions studied are very heterogeneous across the studies. Among the many adaptation alternatives considered, 'better insulation' and 'use of shading devices/blinds' stand out as most frequently cited. Both appear and are quantified in about a third of the papers. Approximately 65% of the papers have a geographical resolution smaller than a country (e.g. states, provinces, or cities), and only a quarter (26%) rely on data at the country scale. Only four articles quantify alternatives at the regional or global scale.

The review finds that the choice of adaptation pathways studied in the papers strongly depends on the scale of the studies and the methodology used. For instance, quantified alternatives are rare among econometrics- or statistics-based papers. In contrast, they are studied in almost half of the papers using integrated or building energy models. It is more difficult to study the consequences of potential changes in technology adoption or behaviors with econometrics models, which are by nature designed to analyze the consequences of existing technologies and behaviors. In some papers, generic measures are studied (e.g. 'better insulation'), whereas in other papers specific actions are documented (e.g. 'mixed mode ventilation'). A direct comparison across the papers is therefore difficult.

3. Demand-side mitigation options vary across end-use sectors and are consistent with well-being

Key strategies include socio-behavioral change, low-carbon infrastructure and service provision, and rapid adoption of low-carbon technologies. These can be broadly mapped into ASI categories.

Demand side options are multifaceted and reach into every part of daily life. A wide array of different aspects are covered in the focus issue. Here, we start with considering an overview on consumption-based options from an individual perspective, then specify the urban contribution, followed by transport, building and food sector perspectives. This is the rounded up by circular economy (CE), material efficiency and digitalization specific reviews, exploring in each case demand-side mitigation options.

The systematic review 'Quantifying the potential for climate change mitigation of consumption options' investigates impacts of consumption options on climate change mitigation, based on a comprehensive screening of **consumption-based footprint studies** (Ivanova *et al* 2020). The study generated an initial sample of 11 626 references from Scopus and Web of Science. After removing duplicates and irrelevant studies, inter alia with the help of machine learning methods, the final sample consisted of 53 relevant studies. It identifies 60 consumption-based mitigation options, categorized in ASI categories, and estimates their potential, as based in the literature, with median and range values. The results can be seen as global benchmark, and are, for example, reflected in the Technical Summary of the IPCC report on climate solutions (Pathak *et al* 2022). A crucial next step is to harmonize consumption-based options as a function of income, culture, and spatial context.

Ivanova *et al* emphasize the importance of considering the full range of impacts of consumption options, including impacts on commuting travel, non-work travel, home energy use, and office energy use. While options appear at individual scale, there are multiple challenges, including technical, economic, and institutional barriers. Overcoming these barriers requires a combination of technological innovation, policy intervention, and behavioral change.

In the domain of transport, the options with the highest mitigation potential include:

1. Living car-free, which has the highest median mitigation potential across all of the reviewed options at 2.0 tCO_2eq/cap, with a range between 3.6 and 0.6 tCO_2eq/cap.
2. Reducing air travel. One less long return flight may reduce between 4.5 and 0.7 (mean of 1.9) tCO_2eq/cap, while taking one less medium return flight can reduce between 1.5 and 0.2 (0.6) tCO_2eq/cap. The two options have a median reduction potential of 1.7 and 0.6 tCO_2eq/cap, respectively.
3. Shifting to less carbon-intensive fuel sources, means, and modes of transportation.

In the context of food, the highest carbon savings come from dietary changes, particularly the adoption of a vegan diet with an average and median mitigation potential of 0.9 and 0.8 tCO_2eq/cap, respectively. In housing, main options include investments

into heat pumps, prosumer renewable energy systems (including balcony solar for renters), and insulation measures.

The mitigation potentials strongly depend on income, as high-income households fly much more and have different consumption patterns. Affluent households not only have more potential to decarbonize their lifestyles, but also more responsibility and more capacity (Nielsen *et al* 2021).

Demand-side solutions are particularly relevant in **cities**, an insight relevant also for the upcoming special report on cities and climate change in Seventh Assessment Cycle of IPCC. The review 'Climate change mitigation in cities: a systematic scoping of case studies' provides an in-depth analysis of urban mitigation solutions and their potential for GHG abatement (Sethi *et al* 2020).

The study identifies demand-side management solutions, including peak shaving or shifting, energy efficiency measures, and retrofitting buildings, as the most frequently investigated interventions. These solutions are crucial for local climate mitigation. Sethi *et al* emphasize the active role of local governments in leading urban climate solutions, either through regulations or partnerships with private or non-governmental actors. Findings suggest that a mix of market mechanisms, user incentives, subsidies, and voluntary measures in cooperation with non-governmental actors is crucial for local climate mitigation.

The study finds that technology-based interventions are more prevalent, with 80% of urban climate solutions being technologically driven. However, it also highlights the importance of combining technological and social experiments to expand and upscale mitigation efforts in urban systems. The highest mitigation values are observed in buildings with net-zero emission buildings (105%), transportation with E-mobility (94%), and waste with waste to energy (87%). However, the performance of certain climate policies, such as the deployment of cool roofs, can vary significantly depending on location. Many of the case studies originated in Europe and China. Crucially, Sethi and colleagues also find that the scale of intervention controls mitigation potential at two levels. Interventions with smaller absolute scope demonstrate greater marginal mitigation potential than more system-wide interventions. The review concludes that urban climate research requires a fusion of disciplinary knowledge to better utilize quantitative and qualitative data on how cities could respond to global warming.

The review titled 'Determinants of low-carbon transport mode adoption: systematic review of reviews' focuses on the factors that influence the adoption of **low-carbon transport modes** (Javaid *et al* 2020). The authors conducted a systematic review of literature reviews, categorizing them into meta-analysis or traditional reviews. They extracted information across these different review types, differentiating between quantitative and qualitative studies. The data extraction process involved two steps: extracting information and judging the quality of information.

The study identified around 75 reviews that fulfilled all the necessary conditions. Thematically, most review studies are linked to infrastructure factors (59 reviews), whereas social factors are lacking in most cases (only 11 review studies). Individual-level factors are also relatively well represented with 32 reviews dealing with these factors. Most of the reviews cover studies from North America, Europe, and Australia. Only 20% of the reviews contain at least one study from Asia or Africa.

From an individual, social, and infrastructure perspective, the study finds that all three dimensions unambiguously interfere with mode choice. Individuals are most motivated to shift modes if they are well-informed, if personal norms match low-carbon mode use, and, most importantly, if they perceive to have personal control over decisions. Perceptions about common travel behavior (descriptive social norms), especially if supported by perceived normative beliefs of others (injunctive norms), are highly influential to support mode shift.

However, the overall margin of shift as induced by individual and social settings remains limited. Instead, the infrastructure factors explain large differences in mode choice. New shared mobility modes, and teleworking and shopping, add a long tail to modes chosen, but are no game changer. The study concludes that a transition to low-carbon mobility requires low-carbon infrastructure, which leverages enthusiastic individuals' concerns and empowers them for mode change, and that address safety concerns prevalent especially in cities of the Global South. The mode shift to low-carbon option can then be sustained and enhanced by social influence in the form of collective social norms.

A more detailed issue is mobility patterns, and in particular the case of avoiding commuting altogether by **teleworking**, an issue that gained increased traction with COVID-19. Accordingly, 'A systematic review of the energy and climate impacts of teleworking' provides a comprehensive investigation of the impacts of teleworking on energy consumption and climate change (Hook *et al* 2020). The study generated an initial sample of 11 626 references from Scopus and Web of Science. After removing duplicates and irrelevant studies, the final sample consisted of 39 relevant studies. The majority of the studies (26 out of 39) suggest that teleworking leads to a net reduction in energy use and/or emissions, with only five studies finding a net increase. These benefits largely result from the elimination of the commute, reductions in congestion, and reductions in office-based energy

consumption. A related review, not in this focus issue, suggests that travel related rebound effects can consume up to one fifth of the emission savings, which still clarifies that telecommuting is largely beneficial to the environment and climate change (Hostettler Macias *et al* 2022).

Hook and coauthors emphasize the importance of considering the full range of impacts of teleworking, including impacts on commuting travel, non-work travel, home energy use, and office energy use, pointing out that the potential for energy and emission reductions through teleworking is often overlooked in climate policy. They conclude that overcoming barriers to telecommuting requires a combination of technological innovation, policy intervention, and behavioral change.

The study 'A map of roadmaps for zero and low energy and carbon buildings worldwide' provides a comprehensive overview of global efforts towards achieving **zero and low energy and carbon buildings** (ZLECB) (Érika Mata *et al* 2020). It maps and classifies 117 roadmaps, policies, and plans from 37 countries. The majority of the documents focus on more developed regions (76% or 325 documents), including Europe subregions, USA & Canada, and Australia & New Zealand. Only 4% of the documents have global coverage.

The most frequent types of documents are recommendations made by researchers and academics to inform policymakers and performance assessment case studies done to establish design practices or prove the efficiency of demonstration projects. The policy objectives include increasing the energy efficiency of new and existing buildings and appliances, encouraging energy distribution companies to support emission reduction from the building sector, targeting attitudes and behavior change, and substituting fossil fuels (FF) with renewable energy sources (RES).

As key demand-side measures, the review specifies the need for effective building design, efficient technical systems, on-site production from RES, and low impact material choices to achieve low energy and carbon during a building's lifecycle. Mata and colleagues identify evidence gaps and clusters, suggesting areas for future research and potential for synthesis via full systematic reviews and emphasize the need for a comprehensive understanding of current efforts, including which measures work and which do not, to avoid wasting funding and resources.

As an accompanying review, 'Systematic map of determinants of buildings' energy demand and CO_2 emissions shows need for decoupling' provides a systematic mapping of the literature on determinants of **energy demand** and CO_2 emissions from **buildings** (Mata *et al* 2021). The authors identify 376 relevant studies and highlight gaps in terms of the studied variables, geographical scope, and methodological approach. The study confirms that worldwide, income, energy price, and outdoor temperature are unequivocal drivers of buildings' energy demand and CO_2 emissions, followed by other indicators of scale such as population or heated floor area. The authors emphasize that decoupling from rising wealth levels has not been observed, which will continue to challenge reductions in energy use and CO_2 emissions from buildings in line with climate targets.

In terms of demand-side climate change mitigation, the study suggests that macroeconomic policies focusing on the impacts of income, energy price, population, and growing floor area are needed in combination with technical policy to reduce the impact of outdoor climate. The authors argue that a comprehensive understanding of the key factors behind buildings' energy use can serve as a basis to define the policy actions most suited to drive the decarbonization of the building sector.

Food stands out as where the largest demand-side potential for GHG emission reduction is located, particulary in diet shift from meat to plant-based diets (Creutzig *et al* 2022a). Correspondingly, the review 'Climate change mitigation through dietary change: a systematic review of empirical and modeling studies on the environmental footprints and health effects of 'sustainable diets' is another important contribution to this focus issue (Jarmul *et al* 2020).

The review systematically investigates the role of dietary changes in climate change mitigation. The authors highlight that the global food system contributes 21%–37% of global GHG emissions, and its impact on the environment is expected to increase substantially by 2050, largely due to population growth and dietary change, particularly in rapidly transitioning economies.

The study identifies the adoption of diets with low environmental impact, often referred to as 'sustainable diets', as an important climate change mitigation strategy. These diets are typically high in plant-sourced foods and low in animal-sourced and processed foods. The review found that switching to 'sustainable diets' results in an average 25.8% reduction in GHG emissions, with vegan diets leading to the largest reduction (approximately 70.3%). However, it also noted an increase in water use associated with these diets. The research is based on 18 studies, encompassing 412 measurements, and highlights the substantial potential for dietary changes to contribute to climate change mitigation and improve health outcomes. The relationship between food systems and climate change is bi-directional, and climate change is currently affecting yields of crops and livestock products and is projected to continue to do so in the future. Hence, demand-side options, such as dietary shifts, can also help to better allocate scarce land resources to human nutrition. Overall, changes in consumer behavior, specifically dietary choices, but

also food waste reduction, can contribute to mitigating climate change at a highly relevant scale.

What can the CE contribute to climate change mitigation? 'Saving resources and the climate? A systematic review of the CE and its mitigation potential' provides a systematic review of the literature on the CE and its potential for climate change mitigation (Cantzler *et al* 2020). The authors conducted a comprehensive literature review, identifying 3244 studies initially, of which 341 (10%) were deemed relevant based on specific mitigation references. The studies were then synthesized and categorized based on sector, geography, resolution, and CE principles.

The document discusses the challenges of synthesizing the mitigation potential of the studies due to the use of different baselines, metrics, and indicators. There is a lack of standardization in the understanding and application of the CE concept, leading to a wide array of measures under the CE umbrella. While the CE concept may serve as a communication tool to accelerate policy action, there is a need for transparency and clarity in its use to avoid confusion and ensure effective climate change mitigation efforts.

Material efficiency is a key CE strategy, relating to demand-side change also within industry. 'Material efficiency strategies to reducing GHG emissions associated with buildings, vehicles, and electronics—a review' presents an extensive review of strategies to enhance material efficiency and reduce GHG emissions (Hertwich *et al* 2019). The authors find that material efficiency could reduce GHG emissions by 12%–21% in the construction sector, 26%–31% in the vehicle sector, and 14%–53% in the electronics sector.

The potential for GHG reduction in the construction sector is mainly due to the reduction in the use of concrete and steel, which are the most emission-intensive materials. In the vehicle sector, lightweight design, car sharing, and longer vehicle lifetimes could significantly reduce emissions. In the electronics sector, the extension of product lifetimes, and the reuse and recycling of components, could lead to significant emission reductions.

Hertwich and colleagues emphasizes the importance of policy interventions to promote material efficiency. The potential for emission reductions through material efficiency remains often overlooked in climate policy. Hence, material efficiency strategies should be integrated into the broader framework of climate policy to achieve significant emission reductions.

On consumer side, it has been long speculated that **digitalization** provides efficiency gains in end use. The review titled 'Digitalization of goods: a systematic review of the determinants and magnitude of the impacts on energy consumption' provides a comprehensive review of the impacts of digitalization on energy consumption (Court and Sorrell 2020), focusing on five categories of goods or services that have been digitalized: e-publications (books, magazines, and journals), e-news, e-business, e-music, and e-videos and games. The study employs a systematic review methodology, including a comprehensive search of literature, screening of titles and abstracts, full-text screening, and data extraction. The search phase generated an initial sample of 12 849 references, which after removing duplicates and irrelevant studies, resulted in a final sample of 31 relevant studies.

The review identifies several examples of potential energy savings due to digitalization in specific technologies. For instance, in the case of e-publications, there's a notable reduction in energy consumption compared to physical books, depending on user behavior and device efficiency. Similarly, digitalization in music and news industries shows a trend towards energy savings when compared to traditional media formats. These savings are context-dependent and vary based on factors like device usage, energy sources, and the displacement of non-digital activities.

4. Behavioral and social interventions and initiatives to reduce GHG emissions

Another set of reviews in the focus section complements demand-side mitigation options with a view on behavioral and social interventions and approaches—society perspectives—on climate change mitigation, revealing the relevance of understanding motivations and rationalities of people both as consumers and as social actors and citizens.

The review titled 'Effectiveness of behavioral interventions to reduce household energy demand: a scoping review' provides a comprehensive review of **behavioral interventions** aimed at reducing household GHG emissions (Composto and Weber 2022).

The authors have conducted a scoping review of 584 empirical papers. The most studied behavioral interventions are providing timely feedback and reminders (258 papers) and making information intuitive and easy to access (246), followed by communicating a norm (158). Electricity use is the most studied target behavior (439 papers), followed by investments in energy efficiency (94), choice in mode of transportation (41), choice of energy source (17), and buying carbon offsets (4).

Similar to other reviews in these focus issue, the authors categorize behavioral changes into three types: ASI. Avoid responses are examined in the most papers (415 papers), followed by shift (112) and improve (77) responses. 72 of the 584 papers included an economic incentive; the choice architecture interventions of reframing consequences (26%) and setting proper defaults (24%) are most frequently combined with an economic incentive. The authors

also discuss the methodological aspects of the studies reviewed, noting the presence of publication bias and the need for larger sample sizes, random assignment, control groups, and field applications. They also highlight the need for future research to routinely measure longer-term impacts of interventions.

Another review and meta-analysis, titled 'Meta-analytic evidence for a robust and positive association between individuals' pro-environmental behaviors and their subjective wellbeing' (Zawadzki *et al* 2020), explores the relationship between individuals' **pro-environmental behaviors** and their subjective well-being. Such behaviors, which are crucial for reducing carbon emissions, can have a significant impact on people's daily lives. The review investigates whether and how individuals' pro-environmental behavior is related to subjective wellbeing, and whether pro-environmental behaviors can be promoted in a way that protects and promotes individuals' subjective wellbeing.

The review finds that fostering pro-environmental behaviors among individuals can be a key strategy for reducing GHG emissions. The relationship between pro-environmental behaviors and subjective wellbeing is positive and robust. This implies that individuals who engage in pro-environmental behaviors tend to experience higher levels of subjective wellbeing. The authors suggest that this relationship may be due to the meaningfulness of pro-environmental behaviors. Specifically, behaviors that are consciously decided and clearly meaningful at the time of performance, such as sustainable purchase decisions, are associated with higher levels of subjective wellbeing. Similarly, indicators of subjective wellbeing that reflect personal meaning, such as a sense of 'warm glow' or eudaimonic happiness, are also strongly related to pro-environmental behavior.

The authors point outs that policymakers can leverage this relationship to design 'win-win' sustainability programs that not only positively impact the environment but also enhance people's subjective wellbeing. It may be beneficial to emphasize how pro-environmental behaviors can enhance, rather than detract from, people's subjective wellbeing to maintain public engagement with pro-environmental programs or policies. Future studies could test which strategies are most effective in emphasizing the meaning of pro-environmental behavior, and to make people aware of the beneficial effects of pro-environmental actions on subjective wellbeing.

In a shift of gear, the review titled 'Is working less really good for the environment? A systematic review of the empirical evidence for resource use, GHG emissions and the ecological footprint' provides a comprehensive review of the relationship between **working time** reduction (WTR) and environmental impacts (Antal *et al* 2021). The authors conducted a systematic review of the literature, including full-text screening, citation snowballing, and coding based on pre-developed criteria. The review identified 15 fully relevant research articles, which were then critically appraised and synthesized.

The document discusses the empirical literature on working time, resource use, and emissions, with a focus on country-level studies that use econometric approaches to investigate the relationship between aggregate working time and environmental indicators. The review found that while WTR can lead to reduced GHG emissions and resource use, the outcomes are highly context-dependent. The environmental benefits of WTR are primarily through decreased incomes and consumption expenditures. However, the study also notes significant variations in results due to different methodologies and indicators used across studies, making it challenging to draw definitive conclusions.

The desire for **status** can drive unsustainable consumption, but also motivate acquiring energy saving goods and services. The review titled 'Status consciousness in energy consumption: a systematic review' explores the relationship between status and energy consumption, and how this relationship can be leveraged for climate change mitigation (Ramakrishnan and Creutzig 2021). The authors conducted a comprehensive review of existing published work that links status to household consumption decisions and behavior across all end-use sectors. They screened 2662 papers and fully reviewed 53 papers that complied with their criteria.

The review identified 23 distinct theories, with the literature most frequently referring to Veblen's theory of conspicuous consumption. The authors also detailed estimations of status-related energy consumption and identified studies that quantitatively relate status to energy-saving behavior or decisions, and studies that relate status to increased emissions. Status can explain up to 20% change in consumption levels or the willingness-to-pay for carbon reducing consumption.

Interestingly, the authors found that major status-related consumption decisions, such as for housing and big cars, are hardly captured by the literature that relates status consumption to energy use and GHG emissions. This is a considerable gap in the literature, omitting major sources of status-related decisions with high carbon footprint.

The paper concludes that framing energy-saving behavior as high status is a promising strategy for emission reduction. Progressive taxation of status items, such as floor space and vehicle size, can effectively internalize the positional externalities and signal social undesirability, but also reduce emissions.

The review titled '**Lifestyle changes** in mitigation pathways: policy and scientific insights' systematically

investigates the relevance of demand-side measures from individual, social, and infrastructure perspectives regarding GHG emission reduction (Saujot *et al* 2020).

The authors argue that changes in lifestyle, driven by individual and societal choices, can create the necessary space for a feasible supply-side decarbonisation within a 1.5 °C emission budget without the need for negative emissions. This implies that demand-side measures, such as changes in consumption patterns and behaviors, can significantly contribute to GHG emission reduction. The review also highlights the importance of policies that influence future lifestyles, their cost-effectiveness, their consequences on well-being, and their legitimacy. Most of the pathways reviewed do not satisfactorily investigate these aspects. Human and social sciences have a lot to say about understanding changes in lifestyles, including their drivers (e.g. household life-cycle, values), constraints (e.g. infrastructure lock-in, social norms), and the dynamics at play.

The study also acknowledges the political nature of mitigation pathways and argues that this should not preclude lifestyle changes from consideration in pathway development. Saujot and colleagues believe that most changes related to technologies and to the socio-technical system are not value-neutral and that acknowledging this can help in developing more effective and acceptable mitigation strategies.

The study 'Movements shaping climate futures: a systematic mapping of protests against FF and low-carbon energy (LCE) projects' provides a comprehensive analysis of protests against both FF and LCE projects (Temper *et al* 2020). It finds that place-based movements are successful in curbing both FF and LCE projects, with over a quarter of projects encountering social resistance being shelved, suspended, or delayed. The research highlights that LCE projects are almost as conflictive as FF projects, with 30% of FF conflicts and 26% of LCE projects being high intensity. Both project types particularly impact vulnerable groups such as rural communities and Indigenous peoples, with Indigenous peoples involved in 58% of the cases analyzed.

Among LCE projects, hydropower was found to be particularly socially and environmentally damaging, leading to mass displacement and large-scale ecosystem transformation. Incidents of repression or violence against protesters and land defenders occurred in one third of cases, with violent responses most common in hydropower, biomass, pipelines, and coal extraction conflicts. Ten percent of all cases involved the assassination of activists.

The study also highlights 'sacrifice zones' in both the FF and the emerging LCE economies. These zones are areas disproportionately affected by environmental hazards and polluting activities due to industrial, extractive, or infrastructural projects. Specific examples include regions affected by coal mining, oil and gas extraction, and hydraulic fracturing. These areas often face significant environmental degradation, health risks, and social and economic impacts. The study highlights that these sacrifice zones are frequently located in marginalized communities, underscoring issues of environmental justice and inequality. The review also identifies the claims and demands coming from project-impacted communities for a socio-environmental justice approach in building low-carbon futures. The data suggests that the energy transition and decarbonization risk producing similarly unequal social burdens unless there is a deeper transformation of the energy system, informed by engagement and co-design with communities on the energy futures they want. Without community engagement and co-design in shaping energy futures, the transition to LCE may reproduce the social inequalities seen in the FF economy.

Last but not least, a review on 'Limiting food waste via grassroots initiatives as a potential for climate change mitigation: a systematic review' focuses on the role of **grassroots** initiatives in reducing food waste and thereby mitigating climate change (Mariam *et al* 2020). From a quantitative perspective, the study found that grassroots initiatives have the potential to reduce GHG emissions by 4.3%–8.2% of the food sector's emissions. This reduction is equivalent to 0.3%–0.6% of total global emissions. The study also found that these initiatives could potentially reduce food waste by 30%–46%.

From a qualitative perspective, the study highlights the importance of grassroots initiatives in fostering a culture of sustainability and reducing food waste. These initiatives often involve local communities and individuals, and they can have a significant impact on social norms and behaviors related to food consumption and waste. By engaging individuals and communities in efforts to reduce food waste, these initiatives can help shift consumption patterns and social norms in a more sustainable direction. Moreover, they can also contribute to the development of infrastructure and systems for reducing food waste, such as food sharing platforms and community gardens. Thus, grassroots initiatives can have significant impacts not only at the individual and community levels but also in terms of broader social and infrastructural changes.

5. Outlook

We here present a comprehensive overview of 22 review papers on demand-side climate change mitigation, highlighting the significant potential of demand-side approaches to complement technology-focused solutions, and emphasizing their contribution to well-being and planetary stability. This systematic and extensive reviews underscore the

essential role of demand-side strategies in achieving climate goals, particularly in the context of the Paris Agreement's objectives. By choosing to aggregate a complete focus issue with systematic reviews and meta-analysis, we here synthesize crucial evidence relevant to understanding of demand-side mitigation's role in climate change efforts.

Forward looking, we suggest that research on demand-side climate solutions should fill gaps in the when, who, how, and where.

When: studying history and narratives can reveal how various societies and cultures have historically implemented practices akin to demand-side climate mitigation and when they shifted away. By examining historical lifestyles, consumption patterns, and social norms, researchers can identify instances where communities naturally engaged in low-impact living, resource conservation, or sustainable practices. Historical examples can provide insights into successful implementation strategies, the role of cultural values in shaping consumption, and the potential for societal adaptation. For example, traditional lifestyles in the Amazonian rainforest strived for harmony with ecosystems and biodiversity and, while impossible to transfer to modern lifestyles, can provide guidance on strategies and mindsets. Historical narratives can also show at what junctures human societies moved away from sustainable to non-sustainable practices.

Who: studies on the political economy of demand-side measures are crucial for understanding how economic and political structures, power relations create role models, influence lifestyle choices and consumption patterns. They shed light on the vested interests that may create a social hierarchy and interdependence that resist changes promoting sustainable living, offering insights into the dynamics that impede the adoption of climate-friendly lifestyles. Key examples include the FF industry, but also intermediate industries, such as suppliers for car manufacturers. Studies may help to identify barriers and develop strategies to overcome resistance from entities benefiting from the status quo.

How: the design of the 'how of the transition' in demand-side solutions for climate change requires an interdisciplinary, full-system perspective. This involves coordinating various elements such as economic incentives, regulatory frameworks, sociocultural changes (including the influence of religions and identities), and the role of physical infrastructures and the built environment. Such an approach needs to be sequenced and coordinated, transcending the scope of individual disciplines or sometimes collaborative disciplinary approaches. Investigating these complex interactions in a controlled setting is challenging if not impossible, but research from a systems' view is nonetheless needed. Technosphere concepts, such as automobility, digitalization, and energy systems, may be in the center of these investigations. This necessitates more collaborative research across disciplines to understand and implement effective demand-side solutions.

Where: the systematic reviews in this focus issues, similarly to other reviews and systematic maps on, for example, cities (Lamb *et al* 2019), is unambiguous in that studies on the Global South are missing. Also, in global south rural density and interdependence of cities and rural geographies and interdependence of formal and informal economies deserve a special attention to avoid uncontrolled penetration of unsustainable practices among new consumer groups. However, as developing countries are still urbanizing and growing in terms of economic activities, studies are urgently needed that explore and substantiate how demand for better services can be provisioned and satisfied, bringing low emissions together with high quality of life.

ORCID iDs

Felix Creutzig https://orcid.org/0000-0002-5710-3348
Joyashree Roy https://orcid.org/0000-0002-9270-8860
Jan Minx https://orcid.org/0000-0002-2862-0178

References

Andrew H, Court V, Sovacool B K and Sorrell S 2020 A systematic review of the energy and climate impacts of teleworking *Environ. Res. Lett.* **15** 093003

Antal M, Plank B, Mokos J and Wiedenhofer D 2021 Is working less really good for the environment? A systematic review of the empirical evidence for resource use, greenhouse gas emissions and the ecological footprint *Environ. Res. Lett.* **16** 013002

Cantzler J, Creutzig F, Ayargarnchanakul E, Javaid A, Wong L and Haas W 2020 Saving resources and the climate? A systematic review of the circular economy and its mitigation potential *Environ. Res. Lett.* **15** 123001

Composto J W and Weber E U 2022 Effectiveness of behavioural interventions to reduce household energy demand: a scoping review *Environ. Res. Lett.* **17** 063005

Court V and Sorrell S 2020 Digitalisation of goods: a systematic review of the determinants and magnitude of the impacts on energy consumption *Environ. Res. Lett.* **15** 043001

Creutzig F *et al* 2018 Towards demand-side solutions for mitigating climate change *Nat. Clim. Change* **8** 260–3

Creutzig F *et al* 2021 A typology of 100,000 publications on demand, services and social aspects of climate change mitigation *Environ. Res. Lett.* **16** 033001

Creutzig F *et al* 2022a Demand-side solutions to climate change mitigation consistent with high levels of well-being *Nat. Clim. Change* **12** 36–46

Creutzig F *et al* 2022b Chapter 5—Demand, services and social aspects of mitigation *Climate Change 2022: Mitigation of Climate Change* (Cambridge University Press)

Creutzig F, Fernandez B, Haberl H, Khosla R, Mulugetta Y and Seto K C 2016 Beyond technology: demand-side solutions for climate change mitigation *Annu. Rev. Environ. Resour.* **41** 173–98

Creutzig F, Hilaire J, Nemet G, Müller-Hansen F and Minx J C 2023 Technological innovation enables low cost climate change mitigation *Energy Res. Soc. Sci.* **105** 103276

Haberl H *et al* 2020 A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, Part II: synthesizing the insights *Environ. Res. Lett.* **15** 065003

Hertwich E G, Ali S, Ciacci L, Fishman T, Heeren N, Masanet E, Asghari F N, Olivetti E, Pauliuk S and Qingshi T 2019 Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review *Environ. Res. Lett.* **14** 043004

Hostettler Macias L, Ravalet E and Rérat P 2022 Potential rebound effects of teleworking on residential and daily mobility *Geogr. Compass* **16** e12657

Ivanova D, Barrett J, Wiedenhofer D, Macura B, Callaghan M and Creutzig F 2020 Quantifying the potential for climate change mitigation of consumption options *Environ. Res. Lett.* **15** 093001

Jarmul S, Dangour A D, Green R, Liew Z, Haines A and Scheelbeek P F D 2020 Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of 'sustainable diets *Environ. Res. Lett.* **15** 123014

Javaid A, Creutzig F and Bamberg S 2020 Determinants of low-carbon transport mode adoption: systematic review of reviews *Environ. Res. Lett.* **15** 103002

Lamb W F *et al* 2021 A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018 *Environ. Res. Lett.* **16** 073005

Lamb W F, Creutzig F, Callaghan M W and Minx J C 2019 Learning about urban climate solutions from case studies *Nat. Clim. Change* **9** 279–87

Mariam N, Valerie K, Karin D, Angelika W-R and Nina L 2020 Limiting food waste via grassroots initiatives as a potential for climate change mitigation: a systematic review *Environ. Res. Lett.* **15** 123008

Mata É, Korpal A K, Cheng S H, Jiménez Navarro J P, Filippidou F, Reyna J and Wang R 2020 A map of roadmaps for zero and low energy and carbon buildings worldwide *Environ. Res. Lett.* **15** 113003

Mata É, Wanemark J, Cheng S H, Ó Broin E, Hennlock M and Sandvall A 2021 Systematic map of determinants of Buildings' energy demand and CO_2 emissions shows need for decoupling *Environ. Res. Lett.* **16** 055011

Nachtigall F, Wagner F, Berrill P and Creutzig F 2023 The built environment and induced transport CO_2 emissions: a double machine learning approach to account for residential self-selection (arXiv:2312.06616v1)

Nielsen K S, Nicholas K A, Creutzig F, Dietz T and Stern P C 2021 The role of high-socioeconomic-status people in locking in or rapidly reducing energy-driven greenhouse gas emissions *Nat. Energy* **6** 1011–6

Pathak M, Slade R, Pichs-Madruga R, Ürge-Vorsatz D, Shukla P R, Skea J, Abdulla A, Al Khourdajie A, Babiker M and Bai Q 2022 Working group III contribution to the IPCC sixth assessment report (AR6)(Technical summary)

Quéré C L, Ivar Korsbakken J, Wilson C, Tosun J, Andrew R, Andres R J, Canadell J G, Jordan A, Peters G P and van Vuuren D P 2019 Drivers of declining CO_2 emissions in 18 developed economies *Nat. Clim. Change* **9** 213–7

Ramakrishnan A and Creutzig F 2021 Status consciousness in energy consumption decisions: a systematic review *Environ. Res. Lett.* **16** 053010

Roy J, Some S, Das N and Pathak M 2021 Demand side climate change mitigation actions and sdgs: literature review with systematic evidence search *Environ. Res. Lett.* **16** 043003

Saujot M, Le Gallic T and Waisman H 2020 Lifestyle changes in mitigation pathways: policy and scientific insights *Environ. Res. Lett.* **16** 015005

Sethi M, Lamb W, Minx J and Creutzig F 2020 Climate change mitigation in cities: a systematic scoping of case studies *Environ. Res. Lett.* **15** 093008

Skea J, Shukla P, Reisinger A, Slade R and Pathak M 2022 *Climate Change 2022. Mitigation of Climate Change. Summary for Policymaker* (IPCC)

Temper L *et al* 2020 Movements shaping climate futures: a systematic mapping of protests against fossil fuel and low-carbon energy projects *Environ. Res. Lett.* **15** 123004

Viguié V, Juhel S, Ben-Ari T, Colombert M, Ford J D, Giraudet L G and Reckien D 2021 When adaptation increases energy demand: a systematic map of the literature *Environ. Res. Lett.* **16** 033004

Wiedenhofer D *et al* 2020 A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping *Environ. Res. Lett.* **15** 063002

Zawadzki S J, Steg L and Bouman T 2020 Meta-analytic evidence for a robust and positive association between individuals' pro-environmental behaviors and their subjective wellbeing *Environ. Res. Lett.* **15** 123007

Energy requirements for securing wellbeing in Switzerland and the space for affluence and inequality

Joel Millward-Hopkins[1], Vivien Fisch-Romito[1], Sascha Nick[2], and Emile Chevrel[2]*

[1]University of Lausanne (UNIL), Lausanne, Switzerland

[2]EPFL, Lausanne, Switzerland

*Corresponding author, joeltmh@gmail.com

Abstract

The idea that human needs should be secured for all people is largely uncontroversial, and recent research demonstrates that decent living standards could be secured for all, globally, with far lower energy and resource use than today. However, little is known about how the energy requirements of decent living vary across countries and subnational contexts, particularly in affluent countries of the global North. Moreover, important questions regarding inequality remain unexplored. Here we advance previous work on energy and wellbeing, using Switzerland as a case study, by decomposing an established net-zero scenario into the energy required to support human needs, and that related to affluence or excess. We estimate Decent Living Energy (DLE) in 2050 at 19.5 GJ/cap (18-26 GJ/cap in varying subnational contexts), making it only ~10% of Switzerland's 2019 energy footprint, and ~20% of the consumption projected in the net-zero scenario. These low estimates show how, with a fairer distribution of energy, Switzerland could dramatically reduce energy consumption while securing DLE for all. More broadly, our results highlight the theoretical potential for affluent countries of the global North to move towards a more just, egalitarian global distribution of energy and resource consumption, while securing wellbeing for their own citizens.

Keywords: Decent living standards, Energy consumption, Energy footprint, Human wellbeing, Inequality

frontiers | Frontiers in Sustainability

TYPE Original Research
PUBLISHED 31 July 2024
DOI 10.3389/frsus.2024.1375271

Check for updates

OPEN ACCESS

EDITED BY
Eleni Oikonomou,
University College London, United Kingdom

REVIEWED BY
Ian Gough,
London School of Economics and Political Science, United Kingdom
Alexander Scheidegger,
OST Eastern Swiss University of Applied Sciences, Switzerland

*CORRESPONDENCE
Sascha Nick
✉ sascha.nick@epfl.ch

RECEIVED 23 January 2024
ACCEPTED 15 July 2024
PUBLISHED 31 July 2024

CITATION
Nick S (2024) Systems perspectives on transforming Swiss housing by 2040: wellbeing, shared spaces, sufficiency, and de-sprawl.
Front. Sustain. 5:1375271.
doi: 10.3389/frsus.2024.1375271

COPYRIGHT
© 2024 Nick. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Systems perspectives on transforming Swiss housing by 2040: wellbeing, shared spaces, sufficiency, and de-sprawl

Sascha Nick*

Laboratory of Environmental and Urban Economics, EPFL, Lausanne, Switzerland

The Swiss habitat—buildings and related mobility—faces multiple interconnected problems which can only be solved together. These include high energy consumption, significant climate impact, excessive material use with low circularity, accelerating urban sprawl and ecosystem destruction, high mobility costs, low inclusion, and mixed wellbeing outcomes. Guided by values of wellbeing for all within planetary boundaries, we propose a normative scenario based on a nationwide moratorium on new construction until 2100, coupled with four simultaneous neighborhood-scale interventions: renovating buildings to achieve energy class A with high indoor environmental quality, creating flexible shared living spaces, ensuring essential daily services are available within each neighborhood, and deconstructing unneeded settlements. Action levers, coordinated efforts on multiple system leverage points, are here combined with rethinking needs satisfiers. Our model predicts that full renovation could be accomplished in 14–18years, significantly reducing labor, energy, materials, and costs both during and after the transition. Furthermore, it could reverse urban sprawl to levels seen in 1935 or even 1885, depending on deconstruction choices. These findings suggest that demand-side policies could be implemented with low risk, enhancing wellbeing, energy resilience, biodiversity, and climate action, thus providing a strong foundation for societal dialog and experimentation.

KEYWORDS

systems thinking, wellbeing, sufficiency, demand-side solutions, low energy demand, reversing urban sprawl, shared spaces, new building moratorium

1 Introduction

The Swiss human habitat, consisting of buildings, open spaces between buildings, and daily mobility induced by the position of buildings, is linked to a wide range of problematic outcomes, making it much harder to reach the goal of wellbeing for all within planetary boundaries.

Habitat-related issues encompass several critical areas. Energy use and associated GHG emissions remain significant concerns (BFE, 2023; BAFU, 2023a). Material use is high, with a low circularity rate of just 6.9% (Circle Economy, 2023). Urban sprawl has been accelerating since 2002, contributing to ecological habitat degradation (Schwick et al., 2018). High mobility use leads to various costs, including accidents (resulting in 15,200 lost life-years in 2020), air pollution, noise, and travel time (ARE, 2023). Additionally, housing-related capital accumulation is unequal, which exacerbates inequality in housing and life outcomes (Bonnet et al., 2014). Wellbeing outcomes are mixed, as reflected in the housing indicators of the OECD Better Life Index (Van Zanden et al., 2020). Similar outcomes are observed in other rich countries.

Using the 1987 definition of the Brundtland Commission, every single one of these issues is a sustainability issue, affecting both current and future generations' ability to meet their needs.

Like in any wicked problem (Rittel and Webber, 1973), the public good here is disputed and viewed from very different perspectives across the political spectrum or by main stakeholders, such as cities and communes, builders and investors, farmers and nature protection groups, companies, scientists, and the general population daily using this habitat. The main issues are also interrelated, and can be seen as symptoms of the same, larger problem. This means they can only be solved together.

In today's public discourse, housing is a prominent topic, appearing in media, political party platforms, and parliamentary debates. It is central in discussions about CO_2 emissions, climate plans, "housing shortage," low vacancies, and rising rental prices. However, a critical examination of current building practices and their effects—such as urban sprawl, car dependency, increasing floor space per capita, wellbeing, needs and satisfiers, sufficiency, and the use of public, private, or shared spaces—is largely absent. Additionally, the political economy of housing and the interconnectedness of these issues remain "hidden" from decision-makers.

In the complex housing system, it is hard to predict how, when, and which new properties will emerge from the interaction of its components: for example new roads will induce more sprawl and more mobility (Torres et al., 2016), or will cause basic services to consolidate in regional centers, thus reducing accessibility (Ferreira et al., 2012).

This paper is grounded in two core values: ensuring wellbeing for all and respecting planetary boundaries. We begin by analyzing system elements and interactions—stocks and flows, feedback loops, and leverage points—to establish the current baseline and dynamics related to these values. Next, we develop a normative scenario aimed at realizing both values. To explore the feasibility of this scenario, we model and test various quantitative assumptions regarding necessary changes in stocks and flows, as well as qualitative assumptions about modifications in feedback loops. Finally, we propose policy interventions based on identified leverage points.

Specifically, we address the following questions: What is the link between housing resource use and resulting wellbeing? What are the current dynamics? What would be the resource impact, in terms of labor, building stocks, and energy, of transforming Swiss housing? What is the potential to reverse urban sprawl?

Given the urgency of the climate and biodiversity crises, we explore low-risk system interventions that can rapidly address the main issues of Swiss housing. "Low-risk" means the transformation relies on widely available technologies, existing trained workers, and current building stocks while reducing material and energy use. Although this transformation would significantly change daily life for a majority of the Swiss population, this magnitude of change is likely necessary to stay within the boundaries set by our core values.

2 Materials and methods

2.1 Overview

Systems analysis: the interconnection of sustainability outcomes related to the Swiss built environment is analyzed using a systems approach, based on insights from literature complemented by three stakeholder workshops conducted by the author, and analysis of Swiss housing data (section 3.1, 3.2). *Modeling*: to quantify possible policy interventions identified in the system analysis, a simple renovation model is developed, simulating construction labor availability, labor productivity, neighborhood-scale renovations, city-level vacancies, and final thermal energy use for heating and hot water (section 3.3). *Calculation*: finally, the potential for urban sprawl reduction is estimated analytically, using the relative change of the Weighted Urban Proliferation (WUP) indicator, calculated on the basis of the output of the renovation model.

2.1.1 Assessing the interconnection of sustainability outcomes

We identified sustainability outcomes and feedback loops from literature, which we supplemented with insights from three stakeholder workshops focused on sufficiency and sharing. These workshops were conducted in Lausanne and Zurich between June and October 2022, each lasting 2 h and involving 21, 18, and 21 participants, respectively. Per workshop, stakeholders represented were (1) participants in a sustainability innovation conference (scientists, students, investors, startups, companies, planners, public authorities); (2) neighborhood and nature protection associations; and (3) climate communication practitioners (designers, journalists, science organizations, public authorities). While participants were representative in terms of age and gender, they were generally more educated and engaged than the general population. Each workshop followed a structured four-step process: an introduction to sufficiency, group deliberation, a plenary discussion of initial impressions, and a written report incorporating participant feedback (Nick, 2023). The results were linked to previous work on sufficiency interventions based on satisfier orders, leverage points, and action levers.

Stakeholders played a crucial role in refining and validating the feasibility and desirability of a sufficiency scenario centered on limiting and sharing housing space. However, they did not participate in the actual modeling process.

2.2 Model design, validation, parameters and assumptions

2.2.1 Model design

We developed a straightforward spreadsheet-based stock-and-flow model to simulate the effects of a potential new building moratorium. This model does not account for feedback loops or interactions between actors; these elements are included in the qualitative analysis and form the foundation for designing interventions and public policies. These policies, in turn, constrain the behavior of actors, creating the appearance of a coordinated societal effort, particularly from the perspective of modeled average behaviors.

The model follows the fundamental principles of converting causal loops into stocks, flows, auxiliaries, and system boundaries (Binder et al., 2004). It covers the period 2025–2100 and includes the availability of skilled construction workers, initial renovation productivity and the learning curve, and population growth, assuming a high growth scenario to test the moratorium under challenging conditions. The model also considers building vacancies needed for neighborhood-scale renovations, where residents temporarily relocate during renovation, and final energy consumption.

The model calculates three renovation constraints: (a) Initially, low residential vacancy rates limit the number of people who can be relocated within an agglomeration for neighborhood-scale renovations. This constraint is temporary, until renovation and shared spaces increase housing capacity. (b) The availability of qualified workers, despite improving productivity, then becomes the limiting factor. (c) Finally, when most residents live in renovated buildings, population growth dictates renovation needs. We assumed that building material availability is not a constraint, as a temporary fivefold increase in Swiss renovation material use would be negligible at the European level.

The outputs include the annual renovated area, floor space per capita, renovation worker productivity, number of years needed for full renovation, "excess" existing space not needed anymore in 2100 (as a basis for estimating the potential for urban sprawl reduction), and final energy for space heating and hot water.

The model has 22 non-redundant inputs, and 16 outputs calculated annually for 2025–2101.

2.2.2 Model validation

To gain confidence in the model, several steps were followed. First, following the Logical/Physical Theory of Spreadsheet Modeling (Isakowitz et al., 1995), the four components were separated to the extent possible: schema (logic), data (parameters and assumptions), editorial and binding (columns and logical-to-physical mapping), with the last component following causal links. Second, the initial parameters were extrapolated from the present. Third, a sensitivity analysis was performed and included in results. Fourth, a simplified manual calculation was used to check the principal results.

2.2.3 Parameters and assumptions

The state of the Swiss habitat in 2021–2022 is described in terms of stocks, flows, and feedback loops in the next section "A systems view of Swiss housing," from which the starting point of the simulation in 2025 is derived. It assumes a population of 9.05 million, a total building stock of 676 km^2, or 74.7 m^2 per capita, of which 46.5 m^2 of private residential space, 3.9 m^2 of secondary residence, 9.3 m^2 of access spaces, and 15.0 m^2 of public space. The specific assumptions are 540 km^2 of residential and 136 km^2 of public space, all estimated as an extrapolation of the trend of the last 6 years. Final energy consumption of the whole building stock (113 kWh/m^2) and the class A target (37.1 kWh/m^2) represent actual consumption (Cozza et al., 2020).

Population assumptions follow the FSO middle estimate for 2025, FSO high estimate for 2050 (based on the fact that longer-term, Switzerland tends to follow FSO's high estimates) with linear interpolation for 2026–2049 (FSO, 2020). To validate the feasibility of the moratorium even with high population growth, we assumed the highest plausible population in 2100 of 14 million, which is ⅓ higher than the estimate of the UN Population Division (2022) or ⅙ higher than Eurostat (2022). Again, linear interpolation is applied for 2051–2099.

Based on the Decent Living Standards body of work (Rao and Min, 2018; Rao et al., 2019; Millward-Hopkins et al., 2020), the minimum decent living space is defined as 30 m^2 for the first person, and 10 m^2 for each additional person in the household. For a two-person household, which is slightly below the Swiss average household size, DLS requires 20 m^2 per person. This also corresponds to the top of the corridor of sustainable consumption (Cohen, 2021). However, if we move to shared spaces, as analyzed in section 3.2.5 and shown in Figure 1, this floor area is actually quite generous, and should provide a higher average material standard of living than today. For example, for a community with 20 residents sharing kitchens, living, play, and working spaces, DLS suggests 220 m^2, or 11 m^2 per person. Our assumption almost doubles this space.

This does not count access space like corridors and staircases, today around 20% of living space, which scales to 4 m^2 per person in our assumption. We assume no private secondary residences (today 3.9 m^2). Public space, today around 15 m^2 per person, consists of offices, schools, hospitals, shops, hotels and restaurants. We assume a 25% reduction in public space, mainly due to less offices (shared spaces, automation, remote work) and less retail (lower material consumption in a sustainable society), respectively the #1 and #3 categories by space use. Including 4 m^2 access and 11 m^2 public spaces, we reach a total needed renovated space of 35 m^2 per person.

During the period 2013–2022, the average number of workers in construction was 315′000 (FSO, 2023c), of which we estimate 90% work in buildings (i.e., not on roads, bridges, tunnels etc.), and of those, 80% will remain in the profession in Switzerland after the moratorium (not move abroad, retire, or change profession). We also assume this number to remain constant and not grow with the population. These assumptions are all rather conservative, and we can be confident at least this number of workers will be available for renovations.

The average worker can renovate 0.06 m^2 per hour, corresponding to nearly 100 m^2 per year. This estimate is based on an average deep renovation cost of CHF 1500/m^2, gross construction wages of CHF 60 per hour, and labor comprising ⅔ of renovation costs. These figures were validated in November 2023 through discussions with experts at the Forum Vaudois du Logement 2023, organized by the cantonal administration. Since renovations currently occupy a small portion of workers' time, primarily filling gaps between new construction projects, we identify two main sources for potential productivity improvements: (a) better planning, organization, skills, and logistics; and (b) A 1000-fold increase in scale per construction site, shifting focus from apartment-scale to neighborhood-scale renovations. We model this learning curve as a logistic function, asymptotically approaching 150% of today's productivity, with a maximum slope of 0.8 and an inflection point after 5 years, with variations explored under sensitivity analysis (section 3.3.1).

Model inputs are summarized in the Supplementary material (New Moratorium Model, cells B21:C56).

2.3 Estimating the potential for reversing urban sprawl

The main measure of urban sprawl used for policy evaluation and planning purposes, both by the European Environment Agency, and the Swiss Federal Office for Spatial Development, is Weighted Urban Proliferation (WUP). It was developed by Jaeger et al. (2010) and Jaeger and Schwick (2014), integrating the three main effects of sprawl: built-up area, dispersion, and land use per person.

In this paper, we estimate the potential for de-sprawling Switzerland by calculating the relative change in the Weighted Urban Proportion (WUP) after renovating buildings and converting housing to shared spaces. Despite a high projected population in 2100, more efficient use

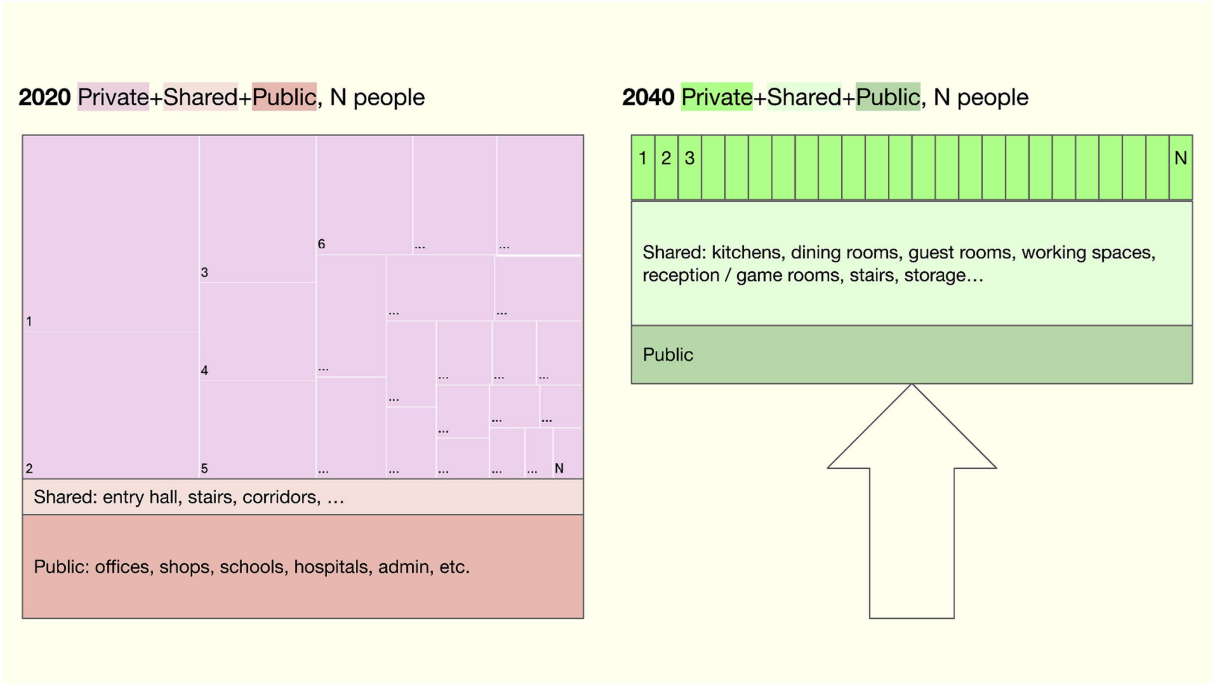


FIGURE 1
Shared spaces can be desirable for two reasons, significant reduction of needed floor space for comparable access through better use of space and lower inequality, and a contributor to wellbeing in itself, as a synergistic satisfier for multiple needs.

of space could result in approximately 27% less total floor area needed compared to 2025 (section 3.3). If buildings were randomly selected for deconstruction until the unneeded 27% floor area is reached, the built-up area would also decrease by 27%. However, optimal selection of buildings that most contribute to sprawl could significantly further reduce both the built-up area and the resulting sprawl.

Our method to calculate the relative change in WUP starts with the Equations 1–3 below, from Jaeger and Schwick (2014), but replaces the two integrals (Equations 2, 3 in the original paper) with a approximated logarithmic Equation 4 fitted to Swiss historical sprawl (Schwick et al., 2018, pp. 76 and 104). The reason for using (4) is that it allows us to estimate the relative change in WUP without the need to calculate the distance of every pair of buildings based on geodata and select buildings for deconstruction (which is a separate project proposed as future research in section 5).

$$WUP = PBA \cdot DIS \cdot w1(DIS) \cdot w2(LUP) \quad (1)$$

$$w1(DIS) = \frac{e^{0.294432 \cdot DIS - 12.955}}{1 + e^{0.294432 \cdot DIS - 12.955}} + 0.5 \quad (2)$$

$$w2(LUP) = \frac{e^{4.159 - 613.125/LUP\left[m^2/cap\right]}}{1 + e^{4.159 - 613.125/LUP\left[m^2/cap\right]}} \quad (3)$$

$$DIS\left[UPU/m^2\right] = 2.2179 \cdot \ln\left(total\ built\ area\left[km^2\right]\right) + 27.714 \quad (4)$$

Where Weighted Urban Proliferation (WUP) is a measure of urban sprawl, expressed in Urban Permeation Units per m² of land (UPU/m²), and is the product of the Percentage of Built-up Area (PBA), Dispersion (DIS), a geometric measure of the average distance of any possible pair of built-up areas, with two weighing factors as S-curves, w1 as a function of DIS, and w2 as a function of Land Uptake per Person (LUP), where persons include both residents and workplaces. The equations are reproduced unchanged from the original references.

All variables are unitless except WUP and DIS, which are measured in UPU/m².

We can now estimate WUP_{2040} from the relative change to 2010 values, which are known, using (Equation 5).

$$\frac{WUP_{2040}}{WUP_{2010}} = \frac{PBA_{2040}}{PBA_{2010}} \cdot \frac{DIS_{2040}}{DIS_{2010}} \cdot \frac{w1(DIS_{2040})}{w1(DIS_{2010})} \cdot \frac{w2(LUP_{2040})}{w2(LUP_{2010})} \quad (5)$$

Known parameters are: total built area in 2010: 2571.04 km²; WUP 2010: 2.474; WUP 1935: 0.870; WUP 1885: 0.376; population in 2010: 7.83 M; jobs in 2010: 3.36 M (Schwick et al., 2018).

The relative change in PBA serves as the input parameter for this estimate. It represents the remaining built-up area after renovations and the deconstruction of unneeded buildings, with materials reused and previously sealed ground restored. This change will range from a linear relationship (where x% of unneeded floor space results in x% less ground coverage, as would occur with a random selection) to a higher multiple if predominantly smaller buildings with relatively large ground footprints, such as single-family houses, are selected for deconstruction (section 3.3).

The remaining parameters for 2040 include a population of 10.57 million, based on the FSO high estimate (FSO, 2020), and 3.00 million FTE jobs, assuming a 10% reduction due to increased remote and flexible work.

The other components of (5) are calculated based on (2), (3), and (4).

3 Results

3.1 A systems view of Swiss housing

We propose three levels of systems analysis to better understand the Swiss habitat: (1) linking physical stocks and flows to human and non-human wellbeing outcomes, (2) understanding how positive (reinforcing) and negative (balancing) feedback loops lead to emergent properties and major housing issues, and (3) exploring how leverage points, and the more recent concept of action levers—coordinated action on multiple leverage points—could inform policy actions to simultaneously solve major housing challenges.

3.1.1 Perspectives taken

As housing shapes societies at many levels, a systems analysis of housing could complement physical stocks and flows (spaces, energy, materials, labor) with multiple societal perspectives, such as degrowth, justice, inequality, wellbeing and human needs, or power and governance.

The transformation proposed in this paper could be considered firmly aligned with degrowth, being a "radical political and economic reorganization leading to reduced resource and energy use" (Kallis et al., 2018, p. 1), aiming to "to conceive and embody alternative ideas, explanations, practices, and institutions today," to prevent the end of growth causing "a state of continual economic depression in which islands of wealth are sustained in seas of deprivation, without pretense of democracy and social justice." (Kallis et al., 2018, p. 19).

More specifically, while historically cities have been primary enablers of growth, today's mainstream urbanism continues to reinforce this role as a driver of innovation for future green growth. This is achieved through energy-efficient housing, sustainable mobility, circular economy practices, and digitalization, fostering a collective vision of dematerialized prosperity. However, this perspective overlooks the environmental and human costs of extractivism at all scales—within cities, in surrounding areas, and across global supply chains. This post-growth view advocates for applying principles of justice, and health and wellbeing of humans and ecosystems to areas such as housing, mobility, consumption, and governance, while avoiding rigid urban blueprints (Savini et al., 2022). Following this perspective, we propose general principles to be locally developed through deliberative governance.

Housing inequality has many causes and consequences, especially other societal inequalities, and may be viewed as four partly reinforcing types: market outcome, policy consequence, situation experienced unevenly across populations, or cultural construct (James et al., 2024). While reducing inequalities is the consequence of decent minimum housing and ecological maxima, and not the premise of our approach, the cultural and policy shift to shared spaces we propose should reduce all four inequality types. Figure 1 shows space use based on actual Swiss income-based inequalities.

The primary conceptual framework developed in this paper focuses on wellbeing and human needs, providing a foundation for operationalizing and modeling space, material, and energy requirements.

3.1.2 Physical stocks and flows, and related ecosystem and human wellbeing outcomes

In 2021, Swiss housing consumed 242 PJ or 30% of Swiss territorial final energy. If ground mobility–to a large extent induced by the position of buildings–is included, the proportion rises to 62% (BFE, 2023). GHG emissions of housing were 7.95 Mt CO_2e, or 17.6% of Swiss territorial GHG emissions (BAFU, 2023a).

Over 31 years (1990–2021), GHG intensity per m^2 decreased by 55.7% due to new construction and renovation. However, total GHG emissions saw a smaller reduction of 33%. This smaller reduction is attributed to a 30% increase in population and a 16.9% growth in per capita floor surface area (BAFU, 2023a).

The sector also generated material flows of non-ore minerals of 45 Mt domestically and 64 Mt abroad, resulting in 57 Mt of additions to the (already very high levels of) building stocks, roughly estimated at 335 t per capita or 2.9 Gt, leading to a very low circularity estimated at 6.9% (Krausmann et al., 2017; Circle Economy, 2023).

There were 1.785 million fully or partially residential buildings in Switzerland at the start of 2022, of which 1.012 million (56.7%) single-family houses (FSO, 2023d). Single-family houses represent 21.4% of all dwellings, and house 29.4% of Swiss residents (FSO, 2023e).

This total building stock at the start of 2022, excluding agricultural and industrial buildings, corresponds to a heated energy reference area of about 667 km^2, of 76.3 m^2 per capita, including 46.5 m^2 of private residential space (FSO, 2023b), plus 10.4 m^2 of shared space (mostly corridors and staircases) and 3.9 m^2 of second residences, as well as 15.5 m^2 of public spaces (Wüest Partner, 2023). These average numbers hide significant inequalities, which are discussed below. The main measure of urban sprawl, the Weighted Urban Proliferation (WUP) increased 558% since 1885, the first available estimate, going from 0.376 to 2.474 UPU/m^2 or Urban Permeation Units per m^2 of land (Schwick et al., 2018).

How do these stocks and flows impact human wellbeing? Switzerland has a very high level of wellbeing, measured by WHR (Rowan, 2023), OECD (Van Zanden et al., 2020), or HDI (UNDP, 2022). Housing is generally of good quality: for example 99.98% of dwellings are equipped with an indoor flushing toilet. However, the average housing expenditure is 21.4% of disposable income, ranking Switzerland 30/41 in the OECD, with 1 being the country with most affordable housing in the OECD and 41 the least (Van Zanden et al., 2020). Given current inequalities, this means a sizable minority cannot afford decent living conditions. Beyond the dwelling itself, other indicators of wellbeing are mixed, especially in the civic engagement category, such as low voter turnout (OECD rank 41/41), gender inequality (rank 37/39), or social inequality (rank 31/35) (Van Zanden et al., 2020). We are not aware of any study exploring the links between high individualism of Swiss society, the rather private nature of Swiss housing, mixed civic engagement indicators, and the overall high wellbeing.

It is worth reflecting on the dominant driver of housing resource use, living space per capita, and its impact on wellbeing. Since 1990, housing floor area per capita grew 16.9% (BAFU, 2023a). The main

Swiss energy and climate scenarios, "Energieperspektiven 2050+," imply a further growth in all categories of housing (single-and multi-family housing, second residences) and a 10% increase of total heated area over the next 2–3 decades (Kemmler et al., 2021, p. 176). So how is this significant increase in floor area, and related material and energy resources, affecting wellbeing? The overall subjective evaluation of quality of life in Switzerland is high but stable, which is also true for the subjective evaluation of satisfaction with housing, measured since 2008 when it was 8.5, stable over time and almost unchanged in 2021 at 8.4. Satisfaction with housing is slightly lower for disadvantaged groups, such as young people (8.1), renters (8.0), or non-Swiss men (7.8), presumably related to the high housing expenditure (FSO, 2023a).

More generally, floor area affects subjective wellbeing through two pathways: space facilitates activities, and space signals wealth and reinforces social status (Foye, 2017). The first pathway shows diminishing marginal returns, which is also the basis for much of the scientific work around decent living standards, which combine basic needs from Doyal and Gough (1991) with Nussbaum's central capabilities, and generally identify a floor of 10–15 m^2/capita (Rao and Min, 2018; Rao et al., 2019; Millward-Hopkins et al., 2020). This is similar to the International Code Council (ICC) minimum of 14 m^2 for the first occupant, and 9 m^2 per additional occupant (Cohen, 2021). Exceeding this minimum may be marginally better, but not if it comes with high costs, as illustrated above, social isolation (Foye, 2017), or commuting beyond a certain distance (Ingenfeld et al., 2019).

On the other hand, status leads to hedonic wellbeing, and this has been well documented (Foye, 2017). A strong determinant of status is relative wealth, which is of course a zero-sum game. For housing, this means that the relative house size matters much more than the objective size, measured in number of rooms or floor space. If the second pathway of social status is indeed dominant for determining subjective wellbeing, as evidence suggests, public policy could achieve much better wellbeing outcomes by focusing on the more equal distribution of housing, and not minimum space standards, as is currently the case (Foye, 2017). This is also supported by evidence showing that prioritization of materialistic pursuits is robustly linked to lower wellbeing, and interventions to reduce materialism may improve wellbeing (Dittmar et al., 2014). Housing size is perceived as positional by ⅓ of respondents (who prefer bigger houses than others, regardless of absolute size), suggesting significant wellbeing benefits of policy to reduce housing inequality (Solnick and Hemenway, 2005).

If the second pathway of status competition could be limited, the total space needed for wellbeing will depend on how the space is arranged and governed, on its quality and flexibility, and on cultural expectations. Shared spaces are discussed below. Beyond a single number, it is also helpful to think of a range, or "consumption corridors," to define the minimum and maximum space, where the maximum is a consequence of the maximum acceptable aggregate consumption to stay within ecological limits, with a preliminary estimate of 20 m^2 per capita (Cohen, 2021).

Taking a historical view, even in the richest countries of the 19th century, living space was very limited: several people per 9 m^2 bedroom was the norm, and 1.5 people per room was considered an unreached ideal (Nelson, 2018). At the same time, while size increase certainly improved living conditions in the beginning, the tripling in house sizes in the US, Canada, and Australia in the last 50 years was more driven by interests of builders, architects, investors, or bankers, than wellbeing concerns (Cohen, 2021). The reason for ever-increasing floor space in rich countries is firmly rooted in the political economy of housing, and in particular the role of housing as financial assets (Cohen, 2021; Zu Ermgassen et al., 2022).

On the other hand, the wellbeing of ecosystems is clearly declining, as summarized in the latest official report, Environment Switzerland 2022: "Switzerland's biodiversity is under pressure… remains in a poor state and continues to decline. A third of all species and half of all types of habitat in Switzerland are threatened. Occasional gains are not enough to make up for the losses caused mainly by a lack of land area, soil sealing, fragmentation, intensive use, and nitrogen and pesticide inputs" (Swiss Federal Council, 2022, p. 84). It is worth noting that the Swiss habitat, i.e., settlements and roads needed to reach them, is the main contributor to fragmentation and soil sealing, i.e., the principal non-agricultural causes of biodiversity loss (BAFU, 2023b).

In summary, the stocks and flows analyzed lead to mixed wellbeing outcomes and a high pressure on ecosystems.

3.1.3 Main positive and negative feedback loops

Almost all developments analyzed in the previous section are shaped by feedback loops, mostly accelerating the underlying processes. Powerful positive feedback loops, often economic or financial in nature, play a significant role. For instance, rising house prices increase returns across the housing asset class, attracting more investment, which in turn boosts demand and drives prices even higher. Standard economic models predict that higher prices should lead to increased construction, which would then stabilize and lower prices. However, due to various restrictions and delays in permits and construction, prices remain high long enough to cause overbuilding, ultimately leading to price drops and increased volatility (Glaeser et al., 2008).

Positive feedback loops can be techno-economic, where increased efficiency—such as in lighting, appliances, or heat pumps—leads to lower costs and various forms of rebound effects, whether embodied or income-based (Chitnis et al., 2013). The rebound effect also contributes to the thermal energy performance gap observed in Swiss buildings. For example, buildings CECB-rated G consume 40% less energy than predicted, those rated F consume 24% less, while more efficient buildings rated B consume 12% more energy per m^2 than anticipated (Cozza et al., 2020).

Techno-economical feedback loops are often structural, such as the example of car lock-in, where several interdependent processes build on each other, in this case (1) the car industry and (2) road builders reinforcing each other, enabling (3) urban sprawl and in the process creating the need for more cars and roads, with all three weakening (4) public transport by absorbing funding and creating hard-to-serve topologies; finally all four creating a (5) car culture based in advertising narratives, new daily practices, normalization of suburban car-centric lifestyles, and association of public transport with poverty (Mattioli et al., 2020).

Once car dependence is pervasive, two more things happen: for most people including decision-makers, it becomes difficult to imagine the end of car dominance, and in an individualistic society where change is first seen as individual action, any action to reduce car use such as taxing cars, road use, or fuel, is seen as socially unjust. This was the main argument used in successfully opposing the June 2021 Swiss climate law referendum, and more spectacularly, the initial

spark starting the massive Gilets Jaunes protest movement in France in November 2018. Indeed, to be just, a transition would require broader intervention: wealth redistribution, dismantling the car lock-in, or probably both.

Each one of the above processes contains its own feedback loops, for example urban sprawl leads to longer travel, more transport dependency, congestion, and pressure to develop new roads. When these roads are built, they cause landscape fragmentation, but also improve accessibility to remote areas and lead to more urban sprawl. In this example, urban sprawl and landscape fragmentation are separate, not always synchronous outcomes, which strongly reinforce each other (Torres et al., 2016).

With the exception of wealth redistribution and dismantling the car lock-in, all the above examples represent positive feedback loops, leading to higher environmental degradation, lower wellbeing, or both. Once established, these processes are not easy to regulate. Building a sufficiently strong negative feedback loop generally requires political mobilization, and in the Swiss political system designed for stability, this mobilization rarely succeeds. One rare successful exception was the initiative on second homes, accepted in 2012 and signed into law in 2015, which requires communes to withhold building permits for second homes if such homes already represent 20% of all housing in the commune (Fedlex, 2015).

In summary, this analysis suggests the existing Swiss housing system structure is stable, with dominant feedback loops reinforcing environmentally and socially problematic outcomes.

3.1.4 Leverage points and action levers

Leverage points are places to intervene to change a system (Meadows, 1999). As high leverage points, like mindset (#2), system goal (#3), power to change system structure (#4), or system rules (#5), are notoriously hard to act upon, a disproportionately large part of public policy focuses on the lowest leverage point, parameters, incentives, standards (#12), often with limited results. On the three examples of sufficiency, negative emissions, and deliberative democracy, "action levers," or coordinated action on multiple leverage points, has been shown to be more effective than focusing on a single high leverage point. Action levers are effective because very small changes in high leverage points, which are feasible without too much resistance but insufficient on their own, can combine and reinforce each other to produce "positive and lasting change to society" (Nick, 2023).

Figure 2 represents Meadows (1999) leverage points, classified in four "realms of leverage" (Abson et al., 2017) indicating the type of intervention. Examples of action levers and suitable combinations of action on multiple leverage points are developed in the next section.

In housing, unsurprisingly, most policy intervention focuses on incentives and standards, such as required energy efficiency of new buildings (effective only over long periods of high construction), or minimum space requirements (ineffective when the dominant pathway to wellbeing is social status, as discussed above). Policy to limit urban sprawl, such as zoning and construction permit guidelines, failed completely, as urban sprawl accelerated after 2002 relative to the historical trend (Schwick et al., 2018).

Renovating inefficient buildings is central: only a fraction of 1% of the total heated area is in efficient buildings of class A, and a further 10% in class B. While only 35 k of 2 M buildings have been assessed for energy efficiency and given a CECB label, this is representative of all Swiss buildings. The renovation focus should be especially on categories C-D-E, together accounting for 78% of the total final energy used (Cozza et al., 2020).

Building renovation is also a major pillar of all Swiss federal and cantonal energy and climate plans, aiming to increase renovation rates from current 0.8% p.a. to at least 1.9% p.a., with some cantonal programs aiming for over 3% p.a. (Cozza et al., 2020; Kemmler et al., 2021). To the best of our knowledge, no canton is currently close to reaching this objective; even with the most favorable assumptions, in the current context, it would be hard to exceed 1.44% p.a. renovation rates (Nick and Thalmann, 2022). There are many local reasons for this gap, from lack of information, variability in return on investment, difficulty to find skilled workers, the principal-agent problem (misalignment of interest between landlord and tenant), but also systemic, large-scale reasons, such as limited workforce skilled in construction and mostly focused on new buildings, and tax incentives favoring materials (and new construction) over labor (and renovation). In other words, even if local problems are solved, renovation cannot easily be scaled to the level needed and planned.

One of the most promising approaches is a new building moratorium, which can take many forms, from a time-and-place bound policy with numerous precedents around the world, all the way to a symbolic worldwide pause to re-imagine our building and caring practices, and stop destruction at all levels and all forms of life: "Until design and planning professionals have figured out how to change their modes of engagement with the built and unbuilt environment, authorities everywhere should stop granting building permits" (Malterre-Barthes, 2025).

From a systems perspective, a new building moratorium represents a powerful system rule (leverage point #5). However, when combined with suitable policy measures designed to foster widespread cultural change, it can achieve much more. It can become a system goal (#3), which limits extraction and contributes to house-sharing, a way of reaching wellbeing for all within planetary boundaries. It can empower communities to establish rules for governing and caring for the building stock and its inhabitants (power to change system structure, #4). Additionally, it can shift stakeholders' mindset (#2) to view the world as an interdependent web of life rather than a resource for profit and growth. Neighborhood governance rules can enhance transparency by improving information flows (#6).

Overcoming obstacles to more radical sharing (Ivanova and Büchs, 2023) and allowing a reduction in total space used can activate additional leverage points. These include creating positive and negative feedback loops around the transition to a new culture of shared spaces and deconstructing urban sprawl. This can reduce the need for transport and break car dependency (#7–8). Furthermore, reusing materials from deconstructed sprawl can lead to the design of new material flows, buffer stocks, and norms of reuse (#10–11-12).

The potential for systemwide improvement is significant. The key question is: how do we design such an intervention effectively?

3.2 Designing a system intervention to solve all major housing issues

Building on the core values defined in the introduction, our proposed low-risk system intervention starts with boundaries derived from these values. The climate and biodiversity emergency necessitates achieving significant results within a decade and climate neutrality and

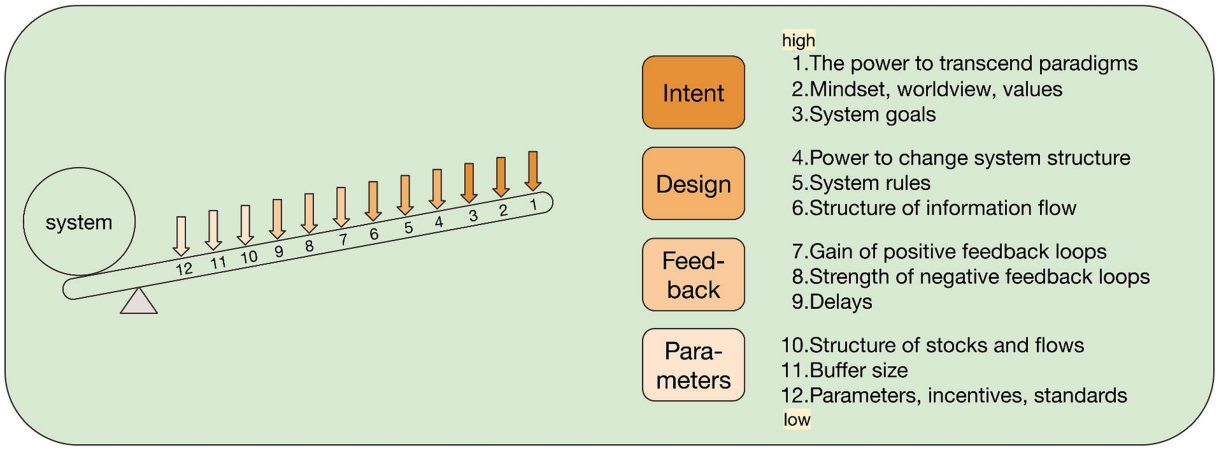


FIGURE 2
Leverage points and "realms of leverage," adapted from Abson et al. (2017) and Meadows (1999), reproduced from Nick (2023).

wide-area ecosystem restoration within two decades. This constraint limits new construction and, together with workforce limitations, directs all resources toward renovation, aiming to complete it within this timeframe. Consequently, this creates a new limit on total building space, necessitating better utilization and, in line with ensuring wellbeing for all, establishing consumption corridors for housing space (Bärnthaler and Gough, 2023). Our analysis suggests that shared spaces increase wellbeing, implying that consumption corridors could incorporate shared spaces. Additionally, to preserve ecosystems, urban sprawl must be reduced, which entails deconstructing part of the existing sprawl, a feasible approach considering needed floor space. This approach follows 'Low energy demand transformations in buildings' as a combination of socio-behavioral, infrastructural, and technological dimensions (Mastrucci et al., 2023).

In terms of interventions, we propose a specific, time-bound new building moratorium focused on Switzerland until 2100. This moratorium is complemented by additional policies to ensure coordination, renovation quality, de-sprawl and material reuse, availability of essential services, and support for people during the transition. Although our model is based on Swiss data, it is likely applicable to any affluent country with a substantial building stock.

Compared to the initial goals, this intervention achieves the transformation slightly faster, with greater de-sprawl and lower energy use than strictly necessary, enhancing its robustness against imperfect implementation and external disturbances. To facilitate societal dialog, we have intentionally kept the intervention straightforward.

3.2.1 Goals of the moratorium, transition resilience

In addition to questioning today's building practice and culture, the new building moratorium serves several essential purposes: (a) refocus existing skilled labor on renovation: transition around 200 k workers, engineers, architects, city planners, etc. from new construction to renovation and remodeling, allowing an acceleration of renovation rates by almost an order of magnitude and a complete renovation to highest efficiency standards of the whole Swiss habitat in <20 years; (b) reinforce existing practices and build a new culture of sharing spaces; (c) significantly reduce the need for new materials, extraction, embodied energy, and ensure resilience under a broad range of conditions, as well as reuse materials available from the deconstruction of existing urban sprawl; (d) create a positive feedback loop of de-sprawl, where available skilled labor, culture of sharing, and widespread reuse of materials reinforce each other, and accelerate the deconstruction of car dependency, based or reversing the process described above.

The actual implementation would require several additional policies and measures beyond the moratorium, with an illustrative overview in Table 1. Here we explore one possible implementation; the actual path must be collectively negotiated. In the Swiss decentralized governance structure, communes would be required to plan renovations for each of their main neighborhoods, engaging residents in a deliberative and participatory process, ensuring essential services are developed in each neighborhood, and helping people transition to avoid any hardship. During renovation, temporary relocation would be organized. Additionally, most low density zones would be planned for deconstruction, reuse of materials, renaturation and restoring ecosystem connectivity.

At the cantonal and federal level, highly progressive taxation on space beyond 20 m^2/cap could create the consumption corridor. Cars, already unneeded following neighborhood repurposing, could be made expensive and less useful, for example by taxes, dismantling roads, repurposing parking, or discontinuing fossil fuel sale. Finally, communes can be supported to ensure they deliver on renovations.

While the framework conditions (outside Swiss housing) during the transition cannot be predicted, it is reasonable to expect further population growth, mainly through immigration, and a certain number of internal and external crises, related to climate, food production and distribution, electricity generation and distribution, health and infectious disease, geopolitical and global supply chain issues, and combinations of these and other factors which are hard to estimate or possibly even imagine today.

For these reasons, the outcome of the transition, as well as the transition itself, must be designed to be resilient: limiting the use of labor, energy, and materials; decentralizing governance and implementation; mostly using locally available resources; and reinforcing the culture of wellbeing, sharing, sufficiency, regeneration, and community. This can be achieved both by creating "quick wins," and through crisis management, should it become necessary.

TABLE 1 A systems overview of possible policy instruments combining neighborhood-scale renovation, unbuilding sprawl, and a new building moratorium.

Goal	Required outcomes	Policy examples	Leverage points
• Net zero before 2050 • Exit fossil fuels	• Reduce floor area per capita by half • Shared spaces as synergistic satisfiers • All buildings reach CECB class A • All fossil fuel heating replaced • Provide all essential services locally to minimize transport • Cars become unneeded, expensive, less useful • No-one is left behind	• New building moratorium until 2100 • Adapt renovation norms to include shared spaces, class A efficiency, local essential services • Communes must plan renovation for major neighborhoods, and include essential services • Highly progressive tax on space beyond 20 m^2/cap • Dismantling of roads, repurposing parking, tax on cars, no fossil fuel sold • Help people transition to avoid hardship	2–3–5-7-8-12 (see Figure 2)
• Reduce urban sprawl to 1935 levels or below • Restore and reconnect biodiversity	• Stop all new sprawl • Reduce total floor area needed • Deconstruct neighborhoods and roads most contributing to sprawl	Low-density zones: Communes must plan deconstruction, material reuse, renaturation and connectivity; cantons guarantee implementation	2–3–5-10
Neighborhood-scale renovation	Relocate people while deeply renovating and re-purposing each neighborhood, and locally creating all essential services	Communes grant renovation permits per neighborhood and organize temporary relocations	5–7-10
Engage population in planning	Communities deliberate and set goals for their neighborhoods, and co-create plans with architects and planners	Renovation planning must include essential local services approved in deliberative assemblies	2–3–4-5-6-7-8

3.2.2 Wellbeing for all within planetary boundaries

Wellbeing is a state of human thriving, based on full participation in society, and a sense of leading a good life. Sustainable wellbeing adds the respect of ecological constraints to extend wellbeing to future generations. Human needs are central to wellbeing and, according to the two main eudaimonic approaches to human needs (Doyal and Gough, 1991; Max-Neef, 1991), these needs are essential to avoid serious harm and deprivation. They are constant across time and cultures, finite, non-substitutable, and satiable. Both approaches differentiate between needs and satisfiers—the means to satisfy human needs. Satisfiers, which can include goods, services, activities, institutions, and relationships, are culturally specific and change over time.

This paper follows a eudaimonic perspective of wellbeing, evaluative of overall life satisfaction, as opposed to momentary happiness (Brand-Correa and Steinberger, 2017). Eudaimonic wellbeing is very different from the dominant concept of "preference satisfaction" which cannot be a good basis for wellbeing, for reasons such as imperfect knowledge, bounded rationality, adaptation, lack of moral distinction, or cultural differences (Gough, 2015, 2017). The same limitations apply to hedonic happiness, based on seeking pleasure, and avoiding fear and pain. Max-Neef (1991) distinguishes singular satisfiers (which satisfy one need), synergistic (satisfy multiple needs), pseudo-satisfiers (give the false sense of satisfying a need), inhibitors and destroyers (impair the ability to satisfy other needs).

Finally, sufficiency, as a central concept of sustainability builds on the satiability of human needs, and is the reason why wellbeing for all within planetary boundaries is possible. Thomas Princen (2005) defines sufficiency as an organizing principle of society, as opposed to today's dominant efficiency, and a basis for wellbeing within ecological constraints.

At a societal level, sufficiency can be defined following IPCC (2022): "Sufficiency policies are a set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human wellbeing for all within planetary boundaries."

For housing, this includes (a) reducing activity levels while ensuring human wellbeing: building less, heating less, using less space, traveling less; (b) respecting ecological constraints, local and planetary, for example by stopping pollution, exiting fossil fuels, reversing sprawl; and (c) adapted organizing principles of society: suitable system goals, rules and policies, collective action, and especially culture.

Sufficiency is widely misunderstood, mostly absent from the public discourse, and when mentioned, often confused with efficiency. As summarized in Figure 3, sufficiency action can take place at multiple levels, with varying effectiveness, based on "satisfier orders" (Brand-Correa et al., 2020). Designing sufficiency intervention for large-scale transformation requires acting on multiple high system leverage points, corresponding to changes in socio-technical provisioning systems and socially and culturally built activities (Nick, 2023).

From the perspective of ensuring no planetary boundaries are transgressed, there is an obvious and a less obvious focus. There is obviously a need to rapidly exit fossil oil and gas for heating, significantly reduce cement use and its impact, and reverse urban sprawl to free and defragment ecosystems, as well as reduce transport energy, materials, and pollution.

Less obviously, our most important lever is cultural, as it shapes mindsets (leverage point #2): a culture of sharing, a culture of wellbeing at the community level, and a culture of regeneration (Lyle, 1994; Gibbons, 2020). Beyond culture as shared ideas, practices, and social behavior, this includes cultural and artistic creation, which to be an effective lever of regeneration, must emphasize community engagement and ownership; allowing it to contribute to physical and social regeneration (Evans, 2020).

3.2.3 Sharing and wellbeing

As we have seen above, housing cannot just be reduced to floor area, materials, CO_2 emissions, or energy use. It is above all an

essential and synergistic satisfier for multiple human needs, subsistence and protection, but in ideal conditions and depending on how it is used also for affection, understanding, participation, idleness, creation, identity, and freedom (Max-Neef, 1991). In the best case, housing can contribute to satisfying all fundamental human needs and significantly improve wellbeing. But it can also be detrimental to health, create stress and tensions, alienate people, generate uncertainty, and require excessive investment in resources or travel time.

Fundamentally, most wellbeing benefits of housing center on interactions with other people, which is not surprising as this is the focus of most human needs, and even the universal societal goal of "minimally impaired social participation" (Doyal and Gough, 1991). On the other hand, most negative impacts of housing are directly or indirectly linked to high resource use.

From the perspective of human needs, shared spaces can be considered a synergistic satisfier, using the same resources to satisfy multiple needs: subsistence (place of work), understanding (setting of formative interaction), participation (setting of participative interaction), creation (productive and feedback settings, audiences, spaces for expression), identity (settings which one belongs to), building on Max-Neef (1991).

Figure 1 shows current use of habitable space per capita, including 46.5 m^2 average private space, shared spaces, and 15.5 m^2 public space per capita, for a total of 76.3 m^2. From a human needs perspective, shared spaces are a synergistic satisfier for subsistence, participation, creation, understanding, and identity. The 2040 representation illustrates what space use could look like after the transformation. By significantly reducing both average private space and its level of inequality, average floor space could be reduced perhaps by half, and most people could have access to all the space they need, most of the time, either by reserving certain spaces such as guest rooms, dining rooms, or party rooms, or by simply sharing with others present at the same time, for example in a shared kitchen or co-working space. This reduces both the time spaces are unused, and inequality of access.

Many forms of shared spaces exist at all scales, from co-living, cooperatives, ecovillages, communes, co-housing, kibbutzim, intentional communities, pocket neighborhoods, and others. Each shared form has its good and bad sides, and most likely this large diversity will continue and expand in the future. While the ecological constraint imposes that average housing should be small, and wellbeing considerations suggest shared spaces, the key question could be formulated as "How compact and how communal?" (Nelson, 2018, p. 7). Of course, the space is just the beginning; just as important is the culture, the shared practices, ideas, values, and learning to live together. As conflict is inherent to sharing, these practices must include conflict resolution. Conflict reduces wellbeing, but overcoming conflict builds trust, shared norms, and social capital, improving wellbeing. This is nothing new; it has been the norm throughout much of human history. It is today's oversized and standardized living arrangements in the Global North that represent the historical exception (Nelson, 2018).

Additionally, and less obviously, shared spaces are one of the most effective ways of rapidly reducing inequalities, which is in itself desirable for wellbeing and trust in society, but is also indispensable for behavior change leading to net zero, which could otherwise cause hardship for disadvantaged people, for example when acting to break the car lock-in (Kukowski and Garnett, 2023). Additionally, empirical evidence from Barcelona shows that willingness to share houses or objects is one of the strongest predictors of life satisfaction (Sekulova and van Den Bergh, 2013).

Sharing spaces could be supplemented by tiny apartments, for people who cannot or do not wish to share, while maintaining similar space per capita. Ensuring equitable access to quality and quantity of living space is crucial for the acceptability and overall success of the transformation.

3.2.4 Supply-side vs. demand-side interventions

While the moratorium is a supply-side policy, its main effect could be as an enabler of demand-side solutions, which are policies, interventions, and measures designed to reduce demand and improve wellbeing at the same time (Creutzig et al., 2022). In addition to decent living standards described under stocks and flows above, it includes scenarios like "High with Low" (HwL), focused on high wellbeing and low energy and material demand, and makes building a decarbonized and resilient energy system, economy, and by extension society feasible, while limiting reliance on unproven technologies like large-scale carbon removal (Sugiyama et al., 2024). This improved (or degraded) resilience is locked-in early through path dependency, with low energy demand leading to multiple benefits such as healthy humans and ecosystems, wellbeing, equity, and resilience. On the other hand, high energy demand would lead to multiple risks such as environmental destruction, pollution, delays, competition for land, or fragile energy systems (Sugiyama et al., 2024). The reason why demand-side solutions work so effectively for wellbeing is that they target not only provisioning systems, as supply-side measures do, but also act on satisfiers, i.e., means through which we satisfy our needs, in effect transforming culture (which can be viewed as the sum of all satisfiers).

While demand-side interventions are highly desirable, they do not materialize automatically by changes in supply. Rather, supply-side transformations may create the conditions for additional policies which would be much more difficult to enact without such transformation. For example, sharing spaces (demand-side) is much easier if dwellings are designed for sharing, where private and shared spaces can easily be separated and reconfigured as needed, and when many people are living in housing designed for sharing, and when large private spaces are culturally seen as unusual and are heavily taxed, therefore expensive. All this needs critical mass, which can only be developed (supply-side) within a decade or two when most construction workers move from new construction to renovation. This can be achieved with a moratorium, which also makes progressive taxation of space to reduce inequality both necessary and more acceptable.

Illustrative policy instruments are developed in section 4.2 and Table 1.

3.3 Renovation modeling results

Our simple model suggests that the main interrelated problems of Swiss housing can indeed be solved together in less than 20 years, using less resources (workers, energy, materials, money) than business-as-usual, every year during and especially after the transition. This holds all four main outcomes of the transformation: housing availability, wellbeing, energy use, and urban de-sprawl.

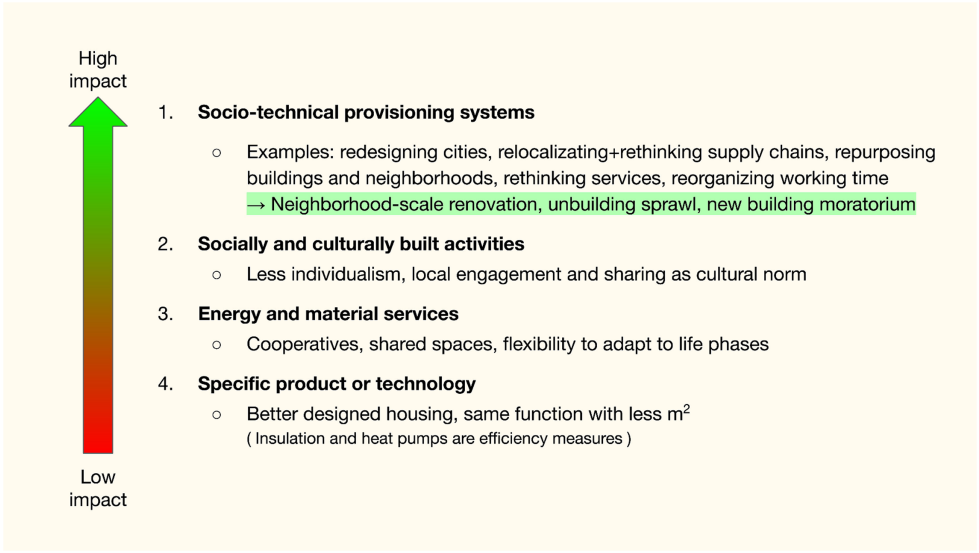


FIGURE 3
Effectiveness of sufficiency action; "satisfier orders" adapted from Brand-Correa et al. (2020).

The proposed transition begins with a nationwide moratorium on new building construction until 2100, redirecting all available construction workers to four coordinated neighborhood-scale renovations: (a) Achieving energy efficiency equivalent to CECB rating A, while ensuring high indoor environmental quality; (b) Repurposing existing residential, office, retail, and other spaces to create neighborhoods where all essential daily services are within short walking distance; (c) Transforming buildings to accommodate shared living and working spaces, reducing private areas, and allowing flexible access to spaces as needed; and (d) Deconstructing neighborhoods that most contribute to urban sprawl and are difficult to repurpose, to reduce overall space to the necessary level and substantially decrease urban sprawl, while reusing materials, removing access roads, and restoring ecosystems. Further assumptions are detailed in the methods section.

Counterintuitively, opposing the dominant public discourse on residential space shortages, a new building moratorium can rapidly and significantly improve housing availability. The current lack of availability, which leads to high housing prices and low affordability, is primarily due to prevailing usage patterns—such as housing inequality and the frequent vacancy of many apartments and most rooms—exacerbated by the treatment of housing as an investment asset class, rather than an actual shortage of space. This perspective aligns with recent systems-based research, such as the study on social housing availability in the United Kingdom by Pagani et al. (2024).

New construction gradually increases the stock of available space, but it can also perpetuate inefficient use patterns. For example, it may increase floor space per person or the number of secondary residences, resulting in either a slow increase or decrease in overall availability, depending on which effect is dominant.

On the other hand, a new building moratorium liberates the large existing skilled workforce to start transforming the existing building stock at an accelerated rate enabling a much more efficient use of space. If coupled with suitable public policy, the physical transformation (systems leverage point #10), incentives to discourage high space use (#12), system rules (#5), and a new culture of sharing space (#2) can create a powerful action lever, and transform the whole built environment and its use in 15–20 years. Under such conditions, Switzerland has more than enough space in existing buildings for its growing population until well beyond 2100, even after deconstructing 20–30% of existing space.

3.3.1 Housing and space availability, wellbeing

In our central estimate, the whole transformation can be completed in 14 years (2025–2039), providing each of the 10.37 million Swiss residents in 2039 with 35 m² of highest indoor environmental quality space, energy class A, as a combination of private, shared, and public space, with little residual inequality.

Figure 4 presents the main results of the simulation. The annual renovated floor area (light green) increases as the obstacle of low vacancies in Swiss cities is overcome. Worker productivity (black stars) rises as the sector focuses on renovation, eventually renovating 53% of the initial stock to meet the population's needs (dark green). As a result, floor area per person decreases and stabilizes (brown dotted line), which together with better efficiency reduces final energy consumption by 82% (orange).

Of the initial total 676 km² of floor space, 360 km² (53.2%) have been renovated by 2039, 130 km² (19.3%) have been identified and reserved for future renovations, one neighborhood at at time, to accommodate the growing population until 2100, and a further 186 km² (27.5%) have been identified as unneeded, progressively deconstructed to reuse materials, as well as liberate and defragment ecosystems.

Today's trained construction workforce in Switzerland is sufficient to renovate the whole needed building stock in 14 years, in the central estimate. This finding is robust and depends little on model assumptions. This period is also the shortest meaningful duration for

a new building moratorium. However, given the numerous uncertainties of such an ambitious program, a 5-year buffer, covering a wide range of parameters, would be meaningful, defining the shortest meaningful initial building moratorium of around 20 years. The moratorium could later be extended, perhaps as an easier political decision than immediately aiming for 2100.

The current annual renovation rate of 0.8% can be accelerated by a factor of five to 3.8% p.a. on average over the 14-year period, with a peak rate exceeding 5% p.a.

3.3.2 Robustness and sensitivity analysis

The main outputs, especially time needed for full renovation and repurposing of the Swiss building stock, change only very little with assumptions. For example, limiting labor productivity increase to 10% extends renovation by 4 years, whereas allowing +100% productivity accelerates by 2 years: range 12–18 years, central estimate 14 years. Changing the number of workers who stay after the moratorium from 80% changes a year or two: 16 years for full renovation with 70% worker retention; 13 years with 90%. Reducing population growth from the high to the central 2050 scenario makes little difference: 14 years, unchanged. Finally, increasing private + shared space requirement by 25% adds 3 years. The main reason for high robustness is that, other than the system goal and moratorium, most assumptions are derived from today's existing best practices.

While wellbeing is not directly modeled, it is highly likely to improve, based on four factors: (a) Availability and affordability of living space, an area where Switzerland is in the bottom third of the OECD ranking, creating stress for disadvantaged groups; (b) Highest indoor environmental quality of living space after renovation; (c) Shared spaces as a synergistic satisfier for participation, creation, understanding, identity, combined with a culture of sharing; and (d) Lower transport stress, time, cost, and pollution. From the perspective of Doyal and Gough (1991), the stronger community, more involvement in local governance, healthier living and less polluted transport environment, and easy access to all essential daily services is likely to improve all three main wellbeing dimensions: participation, health, autonomy.

3.3.3 Energy and material use

Total operational final energy use after the transformation in 2040 is reduced by 82%, relative to 2025, going from 275 PJ to 49 PJ, as a result of sufficiency (−46% used living space based on shared spaces) and efficiency (−67% final thermal energy per m^2 based on renovating the while used building stock to efficiency A).

The total environmental impact of renovation is significantly lower than that of new construction per m^2, typically accounting for only 11% of the materials mass, 25% of the global warming potential, and 30% of the non-renewable energy demand (Hasik et al., 2019). In our central scenario, over a 14-year transition period, the average renovated floor area is projected to be about five times greater than current new construction rates (26 km^2 vs. 5 km^2 annually). Despite providing five times more high-quality floor area annually, accelerated renovation would use only 55% of today's annual new construction material mass. Over this 14-year period, based solely on the embodied energy in materials, this approach would generate 125% of today's GHG emissions and use 150% of today's non-renewable energy. However, final energy consumption would decrease sharply (Figure 4).

Moreover, large-scale utilization of materials from the 27% of floor space that is no longer needed could significantly reduce this impact, likely bringing it below the levels of business-as-usual, even at peak times. After this transformation, the environmental impact of annual renovations to keep up with population growth and necessary maintenance would be a small fraction of today's impact.

Finally, after reducing final operating energy by 82%, the remaining energy demand would be easy to cover entirely with heat pumps, eliminating virtually all residual CO_2 emissions. In 2021, heat pumps generated 4.6 TWh or 17 PJ of thermal energy, almost 35% of the needed 49 PJ (Link, 2022).

3.3.4 Urban de-sprawl

Many good proposals aim to slow urban sprawl, restricting or even blocking new built-up areas, for example the Swiss perspective analyzed in Schwick et al. (2018). Yet proposals to reverse sprawl to a past, much lower level, while improving wellbeing of a growing population are lacking.

Our model enables us to examine which spaces are required to accommodate both the current and expected future populations, as well as which spaces will not be needed until 2100, even with high population growth. In our central scenario, deconstructing the 27% of floor space that is not needed can free significant land for food production and ecosystems, defragment landscapes by removing access roads, reduce energy consumption, and provide materials to renovate the remaining buildings. Furthermore, deconstructing the most sprawled settlements would significantly reduce the costs and impacts of transportation, truly solving together the most intractable problems of housing, territorial planning, and transport.

The effect of such deconstruction on Weighted Urban Proliferation (WUP) can be analytically determined from its definition. WUP depends on three parameters, built-up area, dispersion, and land use per person, which are all much less favorable in single-family zones, especially when linked to a minimum plot size requirement (Wegmann, 2020).

Figure 5 presents an analytical calculation of the potential reduction in the Weighted Urban Proliferation (WUP) indicator of urban sprawl, as a function of remaining built-up area after deconstruction. If 27% of unneeded floor space were randomly distributed and deconstructed, the built-up area would decrease to 73%. Alternatively, deconstructing predominantly dispersed settlements could reduce the built-up area by at least 40%, leaving only 60% of the current built area. These two approaches would reduce Swiss urban sprawl to levels observed in 1935 and 1885, respectively. Exact calculations and mobility reduction modeling are planned for future research, but it is likely that the optimal strategy may involve deconstructing most single-family houses.

4 Discussion

4.1 A holistic view, sufficiency, and wellbeing

We have seen that from a systems perspective, the multiple issues of the Swiss habitat (energy, CO_2, materials, circularity, mobility impacts, inequalities, mixed wellbeing outcomes) all result from the same systems structure, and dominant culture or

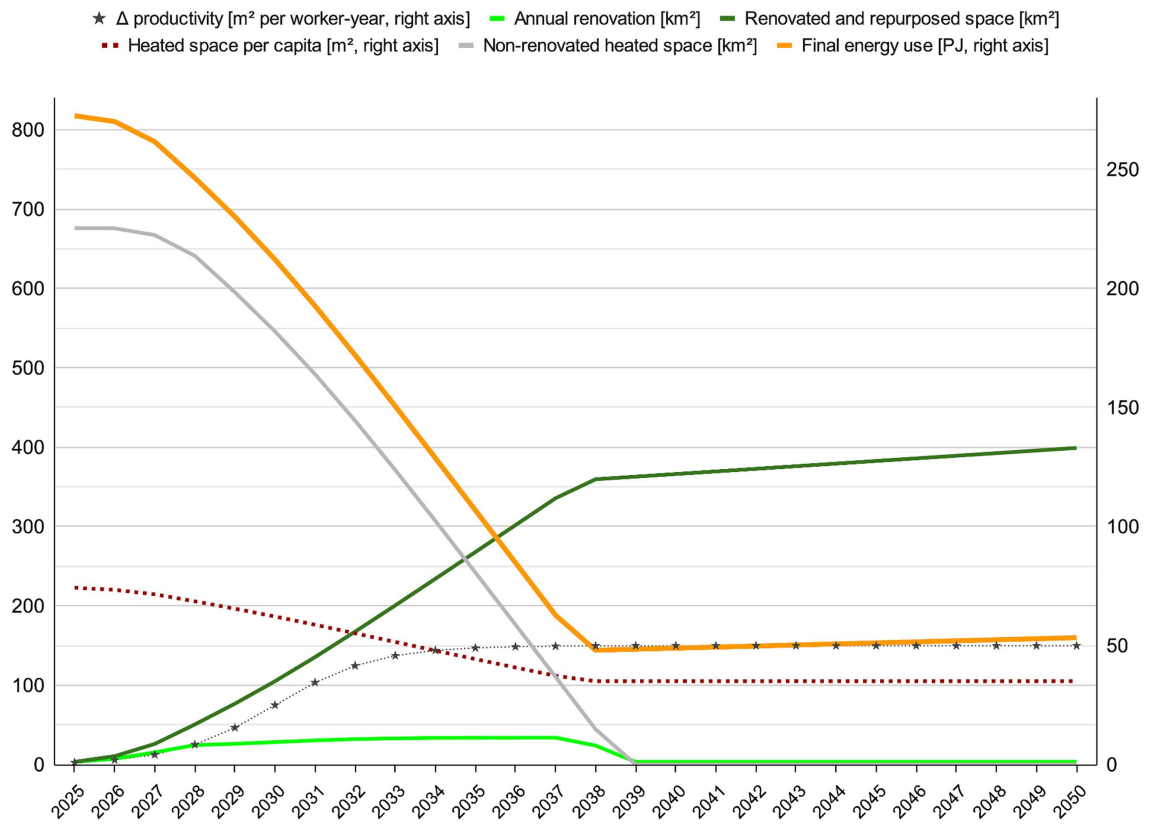


FIGURE 4
Simulation results for the Swiss new building moratorium until 2100, refocusing all available construction workers on four coordinated neighborhood-scale renovations, indicating full transformation can be achieved in 14 years in the central scenario.

mindset (individualism, land and housing ownership structure, power structures around the car lock-in, the imaginaries around single-family houses, profit motivation and housing as a financial asset class, zoning rules, minimum size standards), consistently with the systems iceberg model (Monat and Gannon, 2015). This is especially pertinent if systems structure is primarily viewed as the "cause-and-effect manner in which system components interrelate to yield the system behavior," as recently suggested by Monat and Gannon (2023).

Additionally, the public good is mostly missing from the public discourse, and when discussed, is disputed, as illustrated in the case of sufficiency or biodiversity, making housing issues a wicked problem. Typically, mobility and housing are analyzed separately, and policy is developed independently, but car lock-in and urban sprawl feedback loops show they can only be solved together, or not at all.

Effective climate and energy action requires a mix of sufficiency, efficiency, clean energy, and some CCUS and negative emissions. Such removals being limited to around 10% of current emissions, reaching net zero requires sufficiency, efficiency, and clean energy to cover at least 90% (Nick and Thalmann, 2021). When time is short, much of this reduction must come from sufficiency, today completely absent in housing policy, incentives, or public discourse. Yet sufficiency is closely related to the satiability of human needs, and our three stakeholder workshops showed that effective engagement with the topic is seen by participants as both possible and desirable.

Our model shows sufficiency is essential, given the available workforce and the need to de-sprawl, with a new building moratorium as a possible central leverage point. Extrapolating the current renovation rate of 0.8%, it would take 125 years to renovate the whole building stock, often to less than CECB efficiency A: renovating class F or G to C, D, or E is common. The moratorium forces society and building actors to re-think the value of housing, materials, and labor, as a scarce resource and satisfier of essential human needs, going beyond today's financial reasoning. Refocusing those scarce resources on more valuable outcomes allows to increase renovation peak rates to 5%, and renovate all needed buildings in 14 years to CECB efficiency A.

From the perspective of career planning, a long moratorium has the benefit of engaging construction workers, architects, engineers, and planners to fundamentally rethink their role around caring for the built environment and hopefully its inhabitants.

Wellbeing is a state of thriving, full participation in society, strongly dependent on meeting all fundamental human needs (Doyal and Gough, 1991; Max-Neef, 1991). Consumption levels poorly measure wellbeing, as they ignore the moral distinction of who consumes what and for which purpose, bounded rationality, and cultural differences (Gough, 2015, 2017). In a sustainable society, the needs of all must be met using less resources, making synergistic satisfiers essential. Limiting total living space by stopping new construction creates conditions for widespread adoption of shared spaces, a powerful synergistic satisfier.

Spaces can be shared simultaneously, facilitating participation, as in shared kitchens or children playrooms, or sequentially, by reserving rooms for exclusive use, for example guest or meeting rooms. High levels of access to space while reducing total floor area is possible by reducing the number of empty rooms, which is today a large majority of 16.7 million rooms, or 1.9 average per capita for 8.8 million people (Van Zanden et al., 2020) - i.e. today most rooms are empty most of the time.

Finally, it is important to think of the flexibility of people, not only spaces: as life circumstances change, with births, deaths, recomposed families, or adult children moving in or out, how can people remodel their space use without the disruption of moving?

In summary, we have identified and to a certain extent quantified the main elements needed to solve the wicked problems of housing, with its interrelated symptoms: a systems understanding of the main interactions, the key measures and dimensions of the ecological constraint, housing-related drivers of wellbeing, and promising feedback loops, leverage points, and action levers upon which to build the proposed transition. Two simple models, of the building moratorium and of deconstructing urban sprawl, provide a first test of the feasibility of the approach.

4.2 Policy implications and examples

So far we mainly analyzed one policy measure, the new building moratorium, and discussed system goals and outcomes related to others, such as renovation, governance, or de-sprawl. Table 1 summarizes examples how goals, policies, and outcomes could form an "action lever," i.e., simultaneously action on multiple system leverage points, reinforcing each other (Nick, 2023). This table is just an illustration of possible public policies and a starting point for discussion, not a detailed analysis.

Several combinations of policy instruments could potentially reach the desired outcomes to support the goals. Table 1 covers regulation, incentives, and public investment; it is implicitly assumed culture will follow. But cultural change could also lead the way. For example, will a rich owner of a 1,000 m^2 palace willingly share it with 50 people (cultural change), or just pay a high tax to avoid sharing, thereby subsidizing many poorer people (no change in culture, but new incentives)?

Whichever path is ultimately chosen, sharing-related policies must be designed democratically and equitably, both supply-side (moratorium, renovation policy) and demand-side (culture, sharing, incentives, resource use restrictions).

5 Conclusions, limitations, and a proposed research agenda

This paper addresses a significant challenge: defining, understanding, and simultaneously solving all major issues related to Swiss habitat—particularly energy, climate, biodiversity, accessibility, and wellbeing—well before 2050. Using systems analysis, a simple model of space, renovation effectiveness, labor, an analytical model of de-sprawl, and an initial discussion of potential public policies, we present a comprehensive approach.

5.1 Conclusions

The conclusions are highly promising. Shared spaces emerge as synergistic satisfiers for subsistence, participation, creativity, understanding, and identity. They are deemed acceptable and desirable based on insights from three stakeholder workshops and allow a significant reduction in floor space per capita. This reduction facilitates a nationwide new building moratorium, reallocating the existing skilled workforce to renovations and accelerating these efforts by a factor of five. Additionally, it supports the deconstruction of unneeded buildings, which account for almost 30% of floor space. By wisely selecting neighborhoods for deconstruction, we can reduce Swiss

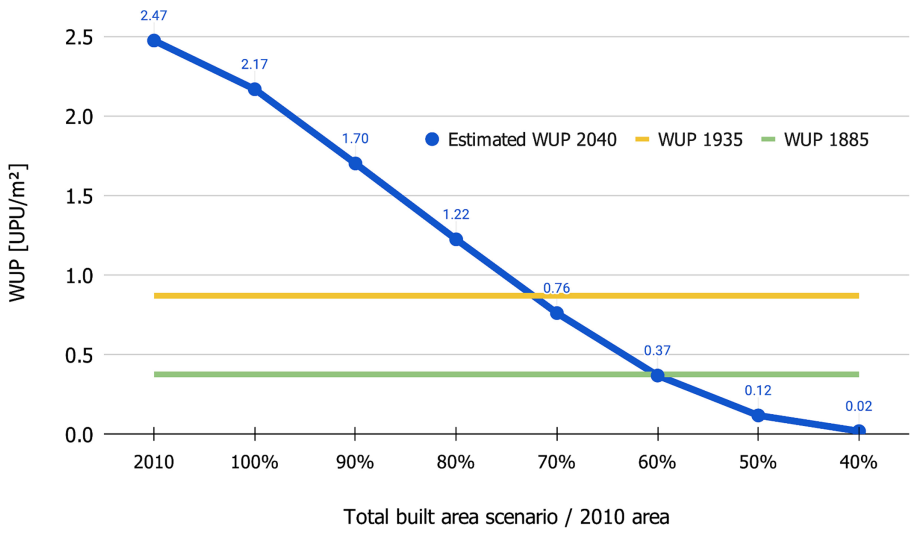


FIGURE 5
Analytical calculation of possible reduction in urban sprawl, expressed as Weighted Urban Proliferation (WUP). Depending on deconstruction choices, the total built area needed is min 60%, max 73%, corresponding to urban sprawl levels in 1885 and 1935, respectively.

urban sprawl to levels seen 100–150 years ago, break the car lock-in, simultaneously solving daily mobility challenges, and provide valuable materials for renovation, significantly enhancing circularity.

Our model indicates that a moratorium on new construction would significantly reduce all necessary building-related resources. Specifically, labor requirements would decrease by 20%, with 80% of workers remaining in the construction sector. Material use would drop by 45% during the 14-year renovation period and by 90% thereafter, while energy consumption would be reduced by 82%.

This resource efficiency suggests that costs per square meter should not increase, and average rental costs could potentially halve due to shared spaces reducing per capita space needs. Operating costs could drop by 80%, significantly enhancing accessibility—a current weak point in OECD comparisons. The 82% reduction in energy use will make oil and gas heating easily replaceable with heat pumps powered by clean electricity, thereby eliminating most CO_2 emissions from heating and greatly improving energy resilience.

Furthermore, reductions in transport time, costs, pollution, and stress, coupled with healthier ecosystems, lower housing costs, better access to shared spaces, and greatly improved indoor environmental quality, should collectively contribute to higher overall wellbeing.

5.2 Limitations

While the systems logic is solid, only space, labor, energy, and sprawl have been quantified using a simple model, and other aspects have only been discussed. They need to be properly analyzed and are here proposed as a research agenda.

Even within the scope of this paper, several limitations exist. The potential of shared spaces is based on literature, three stakeholder workshops, and examples from intentional communities. However, there are few architectural designs of shared spaces for the general population, limiting the generalizability of these findings. The assumed quantity of heated space needed, 35 m^2 per capita, is derived from literature and has not been validated in Switzerland. The analysis adopts a territorial perspective, excluding embodied energy, materials, and emissions from imports. The conversion of final energy to useful heat uses today's efficiency and prevalence of heat pumps, both of which can be significantly improved.

Furthermore, only stocks and flows have been modeled, with much of the systems analysis being qualitative. The nonlinear feedback loops dynamics have not been modeled or quantified. For instance, the question "how much de-sprawling is needed to break the car lock-in?" remains unanswered.

5.3 Proposed research agenda

Beyond the scope of this paper, but important for implementation, there are several key areas or research needed, here proposed as a research agenda:

5.3.1 People

How acceptable are various aspects of a system-wide transformation of the Swiss habitat? Which conditions are needed to increase acceptance? How does this vary by population subgroups? What are the labor and skill implications, beyond the construction workers we analyzed? Which special considerations are needed for rural communities producing food? Will the transformation temporarily cause hardship for some people, and how can this be overcome? How to preserve community links in much-transformed neighborhoods? How to create new social connections? How to best engage communities in deliberation, planning, and governance?

5.3.2 Neighborhoods

Based on spatial analysis and geodata, which criteria and priorities should be used to select neighborhoods for deconstruction? How much de-sprawl, ecosystem defragmentation, car dependency reduction, and material reuse can be achieved? Which regulatory and legal changes are needed? When does property structure need to change, and when is a different governance with existing property structures more beneficial? How to preserve architectural quality and character? Which areas will become vulnerable due to climate change?

5.3.3 Mobility

How can the transformation of the Swiss habitat affect mobility requirements and policies, as well as related policies such as energy, climate, land-use? How can these policies reinforce each other? How can leisure, today's biggest cause of mobility, be transformed to best support high wellbeing with low resource use? Which implications on neighborhoods could this have?

5.3.4 Materials

How suitable are deconstruction materials for renovation, as opposed to new construction, a much more researched area? Which materials, in which quality and quantity, could be reused from the likely main deconstructed neighborhoods, such as single-family houses built after 1960, or shopping malls? Which organizational, legal, economic, informational, or skill and practice obstacles need to be overcome, and how?

5.3.5 Energy resilience

While the habitat transformation will strongly benefit the Swiss energy system, alone it will not solve today's two main issues: crisis resilience and closing the winter electricity gap between high consumption and low generation. What other measures are needed? What will be the impact on the electricity grid of more people living in renovated buildings, with more heat pumps, but also local PV and much higher efficiency?

5.4 Implementation

How to best test, improve, and validate the proposed transformation in real-life neighborhoods? Which conditions are needed for neighborhood-scale tests to happen and succeed? Beyond a successful test neighborhood, how to scale to the needed level in communes, cantons, and nationally? Which policies are needed when?

As often, the solution to complex or wicked problems is not a product, technology, or method. Instead, it begins with dialog and deliberation, perceiving the problem differently, rethinking goals and constraints, and adopting a holistic approach that considers the interactions between parts. This process involves empowering and engaging communities to develop their own solutions guided by the overarching goals of wellbeing for all within ecological limits. This

approach has proven effective at small scales, like in ecovillages or citizens' assemblies. Humanity's future collective wellbeing, and possibly survival, depend on our ability to extend this approach to all. Especially for rich countries extracting resources from abroad, it means including the perspective of all affected communities and ecosystems.

The primary goal of this paper is to initiate this much-needed societal dialog. A systems perspective reveals the extent of change required in habitats and behaviors, with the actual path forward to be collectively negotiated.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SN: Conceptualization, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition, Investigation, Project administration, Software, Supervision.

Funding

The author declares that financial support was received for the research, authorship, and/or publication of this article. The research published in this paper was carried out with the support of the Swiss Federal Office of Energy SFOE as part of the SWICE project. This work was supported by the Energy Demand Changes Induced by Technological and Social Innovations (EDITS) network, an initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and the International Institute for Applied Systems Analysis (IIASA) and funded by the Ministry of Economy, Trade and Industry (METI), Japan.

Acknowledgments

Special thanks to Charlotte Malterre-Barthes for fruitful discussions of the building moratorium, Alexis Dunand for helping develop an early version of the renovation model, Jochen Jaeger for his insights on applying Weighted Urban Proliferation indicators, and Anna Pagani and Matthieu Jaccard for inspiring conversations on architecture, history, systems, inequality, and wellbeing.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2024.1375271/full#supplementary-material

References

Abson, D. J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., et al. (2017). Leverage points for sustainability transformation. *Ambio* 46, 30–39. doi: 10.1007/s13280-016-0800-y

ARE. (2023). *Externe Kosten und Nutzen des Verkehrs in der Schweiz*. Strassen-, Schienen-, Luft-und Schiffsverkehr 2020. Bundesamt für: Raumentwicklung ARE.

BAFU (2023a). *Kenngrössen zur Entwicklung der Treibhausgasemissionen in der Schweiz 1990–2021. Bundesamt für Umwelt BAFU, April 2023*.

BAFU. (2023b). *Biodiversität in der Schweiz - Zustand und Entwicklung*. Bundesamt für Umwelt BAFU.

Bärnthaler, R., and Gough, I. (2023). Provisioning for sufficiency: envisaging production corridors. *Sustain. Sci. Pract. Policy* 19:2218690. doi: 10.1080/15487733.2023.2218690

BFE. (2023). *Schweizerische Gesamtenergiestatistik 2022*. Bundesamt für Energie BFE.

Binder, T., Vox, A., Belyazid, S., Haraldsson, H., and Svensson, M. (2004). *Developing system dynamics models from causal loop diagrams*. In: proceedings of the 22nd international conference of the system dynamic society: 1–21.

Bonnet, O., Bono, H., de La Chapelle, G. F., and Wasmer, E. (2014). *Does housing capital contribute to inequality? A comment on Thomas Piketty's capital in the 21st century*.

Brand-Correa, L. I., Mattioli, G., Lamb, W. F., and Steinberger, J. K. (2020). Understanding (and tackling) need satisfier escalation. *Sustain. Sci. Pract. Policy* 16, 309–325. doi: 10.1080/15487733.2020.1816026

Brand-Correa, L. I., and Steinberger, J. K. (2017). A framework for decoupling human need satisfaction from energy use. *Ecol. Econ.* 141, 43–52. doi: 10.1016/j.ecolecon.2017.05.019

Chitnis, M., Sorrell, S., Druckman, A., Firth, S. K., and Jackson, T. (2013). Turning lights into flights: estimating direct and indirect rebound effects for UK households. *Energy Policy* 55, 234–250. doi: 10.1016/j.enpol.2012.12.008

Circle Economy. (2023). *The circularity gap report Switzerland 2023. Version 1 (March 2023)*.

Cohen, M. J. (2021). New conceptions of sufficient home size in high-income countries: are we approaching a sustainable consumption transition? *Hous. Theory Soc.* 38, 173–203. doi: 10.1080/14036096.2020.1722218

Cozza, S., Chambers, J., and Patel, M. K. (2020). Measuring the thermal energy performance gap of labelled residential buildings in Switzerland. *Energy Policy* 137:111085. doi: 10.1016/j.enpol.2019.111085

Creutzig, F., Niamir, L., Bai, X., Callaghan, M., Cullen, J., Díaz-José, J., et al. (2022). Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nat. Clim. Chang.* 12, 36–46. doi: 10.1038/s41558-021-01219-y

Dittmar, H., Bond, R., Hurst, M., and Kasser, T. (2014). The relationship between materialism and personal well-being: a meta-analysis. *J. Pers. Soc. Psychol.* 107:879. doi: 10.1037/a0037409

Doyal, L., and Gough, I. (1991). A theory of human need. Berlin: Springer.

Eurostat. (2022). *EUROPOP2019 - population projections at national level (2019–2100) (proj_19n)*.

Evans, G. (2020). Measure for measure: evaluating the evidence of culture's contribution to regeneration. *Cult. Led Urban Regen.*, 116–140. doi: 10.1080/00420980500107102

Fedlex. (2015). *Federal act on second homes Second Homes Act, SHA*.

Ferreira, A., Beukers, E., and Te Brömmelstroet, M. (2012). Accessibility is gold, mobility is not: a proposal for the improvement of Dutch transport-related cost-benefit analysis. *Environ. Plann. B Plann. Des.* 39, 683–697. doi: 10.1068/b38073

Foye, C. (2017). The relationship between size of living space and subjective well-being. *J. Happiness Stud.* 18, 427–461. doi: 10.1007/s10902-016-9732-2

FSO. (2020). *Szenarien zur Bevölkerungsentwicklung der Schweiz und der Kantone 2020–2050*. Federal Statistical Office.

FSO. (2023a). *Durchschnittliche subjektive Einschätzung der Lebensqualität, nach verschiedenen soziodemografischen Merkmalen, 2007-2021*. FSO number je-d-20.03.04.01.03. Federal Statistical Office.

FSO. (2023b). *Durchschnittliche Wohnfläche pro Bewohner nach Zimmerzahl, nach Kanton, 2012-2022*. FSO number je-d-09.03.02.04.01. Federal Statistical Office.

FSO. (2023c). *Erwerbstätige nach Wirtschaftsabschnitten und nach Geschlecht, Nationalität, Altersgruppen, Familientyp, 1991-2022*. FSO number je-d-03.02.01.20. Federal Statistical Office.

FSO. (2023d). *Allgemeine Übersicht "Gebäude" nach Kantonen 2022*. FSO number je-d-09.02.00-2022. Federal Statistical Office.

FSO. (2023e). *Verteilung der Gebäude und deren Bewohner nach der Anzahl Wohnungen im Gebäude*. FSO number gr-d-09.02.02-10. Federal Statistical Office.

Gibbons, L. V. (2020). Regenerative–the new sustainable? *Sustain. For.* 12:5483. doi: 10.3390/su12135483

Glaeser, E. L., Gyourko, J., and Saiz, A. (2008). Housing supply and housing bubbles. *J. Urban Econ.* 64, 198–217. doi: 10.1016/j.jue.2008.07.007

Gough, I. (2015). Climate change and sustainable welfare: the centrality of human needs. *Camb. J. Econ.* 39, 1191–1214. doi: 10.1093/cje/bev039

Gough, I. (2017). Heat, greed and human need: Climate change, capitalism and sustainable wellbeing. London: Edward Elgar Publishing.

Hasik, V., Escott, E., Bates, R., Carlisle, S., Faircloth, B., and Bilec, M. M. (2019). Comparative whole-building life cycle assessment of renovation and new construction. *Build. Environ.* 161:106218. doi: 10.1016/j.buildenv.2019.106218

Ingenfeld, J., Wolbring, T., and Bless, H. (2019). Commuting and life satisfaction revisited: evidence on a non-linear relationship. *J. Happiness Stud.* 20, 2677–2709. doi: 10.1007/s10902-018-0064-2

IPCC (2022). IPCC. Climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press.

Isakowitz, T., Schocken, S., and Lucas, H. C. Jr. (1995). Toward a logical/physical theory of spreadsheet modeling. *ACM Trans. Inf. Syst.* 13, 1–37. doi: 10.1145/195705.195708

Ivanova, D., and Büchs, M. (2023). Barriers and enablers around radical sharing. *Lancet Planet. Health* 7, e784–e792. doi: 10.1016/S2542-5196(23)00168-7

Jaeger, J. A., Bertiller, R., Schwick, C., Cavens, D., and Kienast, F. (2010). Urban permeation of landscapes and sprawl per capita: new measures of urban sprawl. *Ecol. Indic.* 10, 427–441. doi: 10.1016/j.ecolind.2009.07.010

Jaeger, J. A., and Schwick, C. (2014). Improving the measurement of urban sprawl: weighted urban proliferation (WUP) and its application to Switzerland. *Ecol. Indic.* 38, 294–308. doi: 10.1016/j.ecolind.2013.11.022

James, L., Daniel, L., Bentley, R., and Baker, E. (2024). Housing inequality: a systematic scoping review. *Hous. Stud.* 39, 1264–1285. doi: 10.1080/02673037.2022.2119211

Kallis, G., Kostakis, V., Lange, S., Muraca, B., Paulson, S., and Schmelzer, M. (2018). Research on degrowth. *Annu. Rev. Environ. Resour.* 43, 291–316. doi: 10.1146/annurev-environ-102017-025941

Kemmler, A., Kirchner, A., Kreidelmeyer, S., Piégsa, A., Spillmann, T., Dambeck, H., et al. (2021). *Energieperspektiven 2050+–Technischer Bericht–Gesamtdokumentation der Arbeiten. Energy perspectives 2050+-technical report-overall documentation of the project work*.

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., et al. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proc. Natl. Acad. Sci.* 114, 1880–1885. doi: 10.1073/pnas.1613773114

Kukowski, C. A., and Garnett, E. E. (2023). Tackling inequality is essential for behaviour change for net zero. *Nat. Clim. Chang.* 2023, 1–3. doi: 10.1038/s41558-023-01900-4

Link, K. (2022). *Statistik der geothermischen Nutzung in der Schweiz*. Ausgabe 2021. EnergieSchweiz, Bundesamt für Energie BFE.

Lyle, J. T. (1994). Regenerative design for sustainable development. New York: John Wiley and Sons.

Malterre-Barthes, C. (2025). Forthcoming. A moratorium on new construction. Cambridge, MA: MIT Press.

Mastrucci, A., Niamir, L., Boza-Kiss, B., Bento, N., Wiedenhofer, D., Streeck, J., et al. (2023). Modeling low energy demand futures for buildings: current state and research needs. *Annu. Rev. Environ. Resour.* 48, 761–792. doi: 10.1146/annurev-environ-112321-102921

Mattioli, G., Roberts, C., Steinberger, J. K., and Brown, A. (2020). The political economy of car dependence: a systems of provision approach. *Energy Res. Soc. Sci.* 66:101486. doi: 10.1016/j.erss.2020.101486

Max-Neef, M. A. (1991). *Human scale development: Conception, application and further reflections*.

Meadows, D. (1999). *Leverage points*. Places to Intervene in a System, 19: 28.

Millward-Hopkins, J., Steinberger, J. K., Rao, N. D., and Oswald, Y. (2020). Providing decent living with minimum energy: a global scenario. *Glob. Environ. Chang.* 65:102168. doi: 10.1016/j.gloenvcha.2020.102168

Monat, J. P., and Gannon, T. F. (2015). What is systems thinking? A review of selected literature plus recommendations. *Am. J. Syst. Sci.* 4, 11–26. doi: 10.5923/j.ajss.20150401.02

Monat, J. P., and Gannon, T. F. (2023). The meaning of "structure" in systems thinking. *Systems* 11:92. doi: 10.3390/systems11020092

Nelson, A. (2018). Small is necessary: Shared living on a shared planet. Chicago: Pluto Press.

Nick, S. (2023). *Action levers towards sustainable wellbeing: Re-thinking negative emissions, sufficiency, deliberative democracy (no. 10487). EPFL*.

Nick, S., and Thalmann, P. (2021). *Carbon removal, net zero, and implications for Switzerland*. E4S Enterprise for Society. Availble at: https://e4s.center/resources/reports/carbon-removal-net-zero-and-implications-for-switzerland/

Nick, S., and Thalmann, P. (2022). *Rapport d'audit du Plan climat vaudois 1ère génération*. Unité du Plan Climat Vaud. Availble at: https://www.vd.ch/fileadmin/user_upload/themes/environnement/climat/fichiers_pdf/Rapport_d_audit_du_plan_climat_vaudois_1e%CC%80re_ge%CC%81ne%CC%81ration_titre-combin%C3%A9_1.pdf

Pagani, A., Macmillan, A., Savini, F., Davies, M., and Zimmermann, N. (2024). *What if there were a moratorium on new housebuilding? An exploratory study with London-based housing associations*. SocArXiv f6suj. Center for Open Science.

Princen, T. (2005). The logic of sufficiency. Cambridge, MA: MIT Press.

Rao, N. D., and Min, J. (2018). Decent living standards: material prerequisites for human wellbeing. *Soc. Indic. Res.* 138, 225–244. doi: 10.1007/s11205-017-1650-0

Rao, N. D., Min, J., and Mastrucci, A. (2019). Energy requirements for decent living in India, Brazil and South Africa. *Nat. Energy* 4, 1025–1032. doi: 10.1038/s41560-019-0497-9

Rittel, H. W., and Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy. Sci.* 4, 155–169. doi: 10.1007/BF01405730

Rowan, A. N. (2023). *World happiness report 2023*. WellBeing News, 5: 1.

Savini, F., Ferreira, A., and von Schönfeld, K. C. (2022). "Uncoupling planning and economic growth: towards post-growth urban principles: an introduction" in Post-growth planning. ed. F. Savini (Abingdon: Routledge), 3–18.

Schwick, C., Jaeger, J., Hersperger, A., Cathomas, G., and Muggli, R. (2018). *Zersiedelung messen und begrenzen: Massnahmen und Zielvorgaben für die Schweiz, ihre Kantone und Gemeinden, no. 57*. Haupt Verlag.

Sekulova, F., and van Den Bergh, J. C. (2013). Climate change, income and happiness: an empirical study for Barcelona. *Glob. Environ. Chang.* 23, 1467–1475. doi: 10.1016/j.gloenvcha.2013.07.025

Solnick, S. J., and Hemenway, D. (2005). Are positional concerns stronger in some domains than in others? *Am. Econ. Rev.* 95, 147–151. doi: 10.1257/000282805774669925

Sugiyama, M., Wilson, C., Wiedenhofer, D., Boza-Kiss, B., Cao, T., Chatterjee, J. S., et al. (2024). High with low: harnessing the power of demand-side solutions for high wellbeing with low energy and material demand. *Joule* 8, 1–6. doi: 10.1016/j.joule.2023.12.014

Swiss Federal Council. (2022). *Environment Switzerland 2022 - report of the Federal Council, FOBL Bern*.

Torres, A., Jaeger, J. A., and Alonso, J. C. (2016). Multi-scale mismatches between urban sprawl and landscape fragmentation create windows of opportunity for conservation development. *Landsc. Ecol.* 31, 2291–2305. doi: 10.1007/s10980-016-0400-z

UN Population Division. (2022). *World population prospects 2022: summary of results*. UN DESA/POP/2022/TR/NO.

UNDP. (2022). *Human Development Report 2021/2022*. Uncertain Times, Unsettled Lives: Shaping our Future in a Transforming World. UNDP/Human Development Report Office.

Van Zanden, J. L., Rijpma, A., Malinowski, M., and Mira D'Ercole, M. (2020). *How's life? 2020: Measuring well-being*. How's Life?

Wegmann, J. (2020). Death to single-family zoning… and new life to the missing middle. *J. Am. Plan. Assoc.* 86, 113–119. doi: 10.1080/01944363.2019.1651217

Wüest Partner. (2023). *Aktualisierung Energiebezugsflächen. Projektnummer 100 044, Nov. 2023. Auftrag Bundesamt für Energie BFE*.

Zu Ermgassen, S. O., Drewniok, M. P., Bull, J. W., Walker, C. M. C., Mancini, M., Ryan-Collins, J., et al. (2022). A home for all within planetary boundaries: pathways for meeting England's housing needs without transgressing national climate and biodiversity goals. *Ecol. Econ.* 201:107562. doi: 10.1016/j.ecolecon.2022.107562

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

February 2025
Prepared for RITE
by Institute for Future Initiatives,
University of Tokyo

Table of Contents

1 EDITS MCE transport protocol 2
1.1 Background 2
1.2 Research Aim 2
1.3 Harmonize the model interaction 3
1.4 Scenario 3
1.5 Model linking details 4
1.6 Output of IAMs 5
1.7 Reference 5

1 EDITS MCE transport protocol

1.1 Background

Factors that directly affect transport demand are currently insufficiently represented in integrated assessment modelling (IAM) approaches and thus emission reduction pathways. Improving the comprehension and impact of diverse factors that affect transport demand in global energy systems models, by incorporating features of complementary models with high demand-side resolution representations of transport, holds promise for generating well-informed policy recommendations. Accordingly, policies could influence the trends and composition of specific relevant drivers themselves and their potential role in mitigating climate change. (Thomas et al., 2024)

The energy demand and carbon emissions from transport is closely linked to the services mobility provides, the way users interact with the technology, and above all the infrastructure that transport system is operating in. The ultimate impact of a given trend may lead to a reduction, but also an increase of emissions, depending on the spillover effects. The increase of shared modes of transport may lead to mode shift effects, i.e. cheaper and more convenient individual mobility - even if in shared cars - and therefore could weaken the competitiveness of public transport, which may lead to an overall increase of vehicle-km, and offset the environmental benefits of mode shift (Yin et al., 2019). For example, Oh et al., (2020) found that the introduction of shared vehicles in Singapore could lead to a doubling of the current number of taxis and a shift from public transport to shared taxis, resulting in a 17 per cent increase in passenger-km. The mode-shift effects involve high uncertainty and could also be insignificant in some areas. For instance, Martinez and Viegas (2017) found that the introduction of fully self-driving cars would significantly reduce the use of private cars, buses and taxis, and eventually reduce total mileage and emissions.

This EDITS model complementarity protocol is to give guidance on how to complement large energy-system models with detailed demand projection models in order to compare the system level impacts of rolling-out shared mobility across IAM models.

1.2 Research Aim

The aim is to evaluate the potential impacts of shared mobility in transport sector decarbonization, especially to assess the modal-shift effects. It will allow to investigate how to incorporate a deeper

understanding of the direct and systemic effects of transportation modal shifts to inform energy system policies

1.3 Harmonize the model interaction

In this study, we mainly consider passenger road transportation, including cars and bus (Akimoto, et al., 2022a). The cars will be further distinguished into shared and non-shared. In terms of mode matching with PASTA, the shared car includes taxi, ridesharing, and car-sharing, while bus includes general bus and on-demand taxi bus, according to PASTA-GUM (ITF Global Urban Passenger Transport Model).

PASTA considered carbon cost and emission of vehicles during the modal shift optimization, and these parameter assumptions should be same as that in DNE21+.

Mandatory: carbon price. Optional: energy price, energy efficiency.

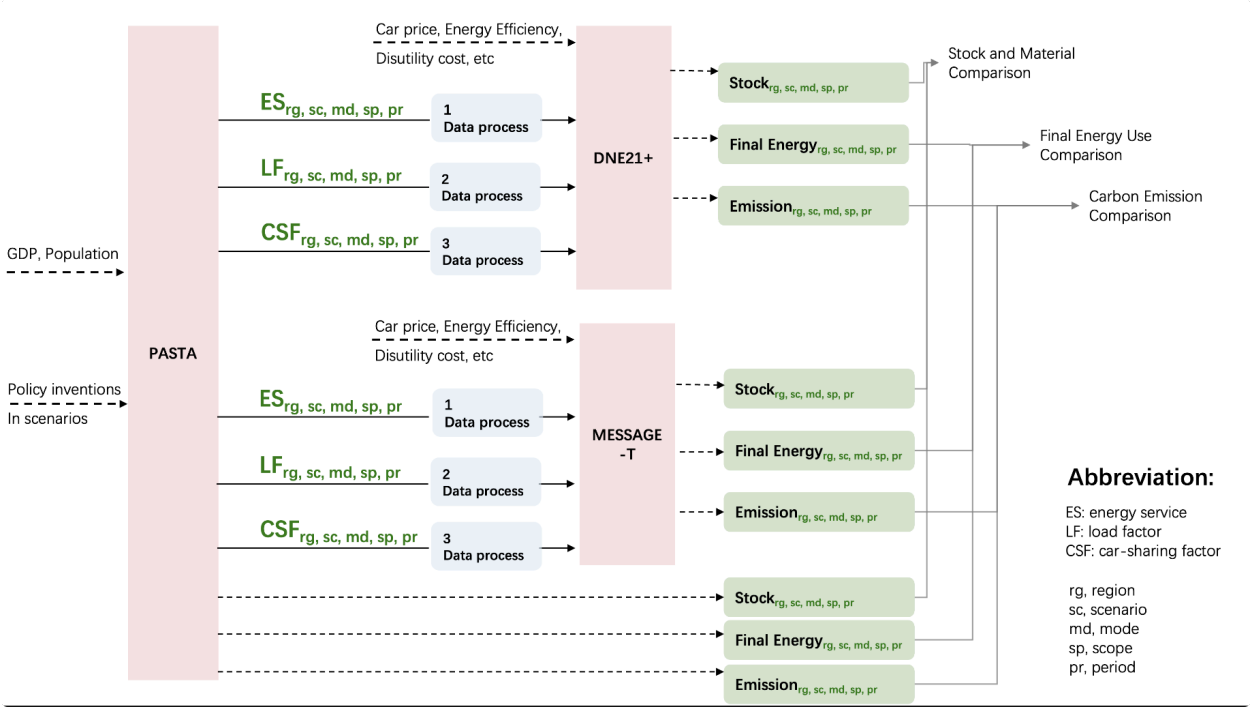


Figure 2.1. Workflow of the MCE transport

1.4 Scenario

We mainly consider current and high ambition according to Trouvé et al., (2024, draft version).

The ambitious policy scenario is aligned with the “high well-being with low energy and material resource consumption (High-with-low)” scenario, a thematic narrative and quantitative framework that imagines a world rapidly racing to achieve the UN Sustainable Development Goals (SDGs) and Paris Agreement.

Table 1. Shared mobility related assumptions and parameters for adjustment or harmonization

Measures	Variables	Current Ambition	High Ambition
Vehicle sharing incentives	Load factor	See Trouvé et al., (2024, draft version)	See Trouvé et al., (2024, draft version)
Ride sharing and shared mobility	Vehicle sharing	See Trouvé et al., (2024, draft version)	See Trouvé et al., (2024, draft version)
Economic instrument	Carbon pricing	See Trouvé et al., (2024, draft version)	See Trouvé et al., (2024, draft version)

1.5 Model linking details

The output from PASTA should include the passenger demand in passenger kilometers and the vehicle demand in vehicle kilometers, as shown below.

Table2. Requested data from PASTA

Variable	**Unit**	**Note**
Energy Service|Transportation|Passenger|Road|LDV	billion pkm/yr	
Energy Service|Transportation|Passenger|Road|LDV|Private car	billion pkm/yr	
Energy Service|Transportation|Passenger|Road|LDV|Shared		Includes tax, ride-sharing and carsharing
AND add occupancy rate / load factor	billion pkm/yr	
Energy Service|Transportation|Passenger|Road|Bus	billion pkm/yr	

Energy Service|Transportation|Passenger|Road|Bus|On-demand taxi bus	billion pkm/yr
Energy Service|Transportation|Passenger|Road|Bus|General bus	billion pkm/yr
Price|Carbon	US$2010/t CO2

Note that Akimoto et al. (2022b) changed the fraction of shared vehicles versus privately owned vehicles and the load factor to represent car- and ride-sharing.

1.6 Output of IAMs

The outputs for comparison include final energy of different transport mode (Shared/Nonshared cars, bus) and vehicle type (ICE, HV, PHV, EV, FCV etc.), related emission and saved materials due to less private car demand.

1.7 Reference

Oh S, Seshadri R, Azevedo C L, et al. Assessing the impacts of automated mobility-on-demand through agent-based simulation: A study of Singapore[J]. Transportation Research Part A: Policy and Practice, 2020, 138: 367-388.

Martinez L M, Viegas J M. Assessing the impacts of deploying a shared self-driving urban mobility system: An agent-based model applied to the city of Lisbon, Portugal[J]. International Journal of Transportation Science and Technology, 2017, 6(1): 13-27.

Yin, B., Liu, L., Coulombel, N., Viguié, V., 2018. Appraising the environmental benefits of ride-sharing: The Paris region case study. Journal of Cleaner Production 177, 888–898. https://doi.org/10.1016/j.jclepro.2017.12.186

Akimoto, K., Sano, F., Nakano, Y., 2022a. Assessment of comprehensive energy systems for achieving carbon neutrality in road transport. Transportation Research Part D: Transport and Environment 112, 103487. https://doi.org/10.1016/j.trd.2022.103487

Akimoto, K., Sano, F., Oda, J., 2022b. Impacts of ride and car-sharing associated with fully autonomous cars on global energy consumptions and carbon dioxide emissions. Technological Forecasting and Social Change 174, 121311. https://doi.org/10.1016/j.techfore.2021.121311

Thomas, H., Serrenho, A.C., 2024. Using different transport modes: An opportunity to reduce UK passenger transport emissions? Transportation Research Part D: Transport and Environment 126, 103989. https://doi.org/10.1016/j.trd.2023.103989

Integrating Transport Demand and Fleet Modelling: Regional Dynamics in Decarbonization Pathways

Andreas Kopf[1*], Matteo Craglia[1], and Luis Martinez[1]

[1] International Transport Forum, Paris, France

* Corresponding author: andreas.kopf@itf-oecd.org

Abstract

This paper explores the integration of transport demand and vehicle fleet modelling to inform policy making on the impact of various decarbonization scenarios. As transport demand continues to rise, CO_2 emissions begin to decouple primarily through advanced vehicle technologies. However, the adoption of new low-carbon vehicle technologies is constrained by the rate of fleet turnover. Vehicle fleet dynamics differ across regions, yet these variations are seldom considered in global energy models. While developed economies or countries with substantial automotive manufacturing capacities typically renew their fleets through new vehicle sales, while other regions in emerging markets are particularly reliant on used vehicle imports, This paper underscores the critical need to account for regional differences in vehicle fleet dynamics when modelling transport and energy systems, emphasizing the role of regional disparities in shaping effective decarbonization policies.

Keywords: transport demand · fleet turnover · used vehicles · global energy model

Evidence is clear: Mitigating Climate Change through demand side solutions puts less burden on the society

Authors: Jingjing Zhang, Joyashree Roy, Michelle Johnson-Wang, Niamir Leila, Nan Zhou, Firuz Ahamed Nahid, Souran Chatterjee, MARTINEZ Luis, ITF/RC, Eric Masanet ,BOZA-KISS Benigna, Shreya Some, Huzaifa Butt

Abstract:
Studies show that demand-side solutions have high potential for mitigating climate change while enhancing well-being and supporting the sustainable development goals (SDGs). But at what cost? This study fills this knowledge gap by developing a comparable assessment framework, identifying a set of metrics for end-user energy services across developed and developing countries, and collecting comprehensive data across energy demand sectors. With a focus on energy services, we present insights for four end-use sectors -buildings, transport, food, and industry, their energy and CO_2 emissions reduction potentials, and monetary costs. Our study clearly shows across the regions, early adopters of demand side solutions are already enjoying as high as 90% and at the minimum 10% cost savings without compromising end-use service satisfaction compared to respective baselines. Our findings indicate that the highest energy, emissions and cost savings are achieved in the building sector, ranging from 10% to 90%, followed by the industry sector, with 30% at the highest. While the transport sector demonstrates clear counterfactual energy and emissions reduction, cost increases are observed in certain highly developed regions. In the food and nutrition sector, there are instances of increased cost, energy, and emissions due to a) regional and rural-urban differences in current access to balanced diet in baseline ;or b) prevalence of unhealthy, unsustainable, unbalanced and wasteful dietary practices. This study provides a comprehensive cost and potential assessment across all demand sectors, offering valuable insights for policymakers, businesses, and citizens to guide decision-making and implementation.

Keywords: climate change mitigation, low energy demand, high well-being, costs and potential, technology, behavior, infrastructure

Inertia in consumer's choice of a suitable contract and consumption patterns in the electricity market

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

SUMMARY

The abstract of the contribution is as follows: Fixed-term retail energy contracts protect end users from market fluctuations but can create market distortions, implicitly subsidizing consumption when prices increase. Imperfect information, inattention, and adjustment costs can affect the targeting of these implicit subsidies and their impact on efficient energy use. Using high-frequency consumption and billing data from an Italian utility, we study the behavior of consumers being defaulted from fixed-price into variable-price contracts during a period of high prices. We find that electricity demand is rather inelastic. Consumers adapt their consumption to price shocks with persistent lag and show limited awareness of their contract status. Their reaction also includes, to a small extent, searching the market for better offers. Fixed pricing helps prevent bill defaults and installment payments. We show that fixed-price contracts could have distributional implications by favoring smaller households with lower energy consumption per occupant.

Distributional Impacts of Demand-side Technological Innovations in three Advanced Economies

Cassandra Etter-Wenzel[1] **and Charlie Wilson**[1,2]

[1]Environmental Change Institute, University of Oxford, Oxford, UK
[2]International Institute for Applied Systems Analysis (IIASA), Luxemburg, Austria
[1]e-mail: cassandra.etter-wenzel@ouce.ox.ac.uk, charlie.wilson@eci.ox.ac.uk

ABSTRACT

Demand-side technological innovations can significantly impact household energy costs through 2050, yet their distributional effects under different adoption scenarios remain poorly understood. In this study, we analyze how technology adoption rates and their associated cost impacts vary across income deciles in three advanced economies. We use comprehensive household survey data to establish current adoption baselines for key technologies including electric vehicles, home retrofits, and solar PV.

We find that under baseline scenarios, energy technologies show varied adoption impacts across countries, with the US experiencing declining costs (-12% by 2050), while the UK and Germany face increasing energy bills (+10-15% by 2050). Counterintuitively, back-loaded scenarios (delayed adoption) consistently result in 3-5% lower annual energy costs than the baseline across all countries studied, while front-loaded scenarios (accelerated early adoption) initially increase costs by 5-8% before potentially delivering benefits after 2040. This suggests significant opportunity costs associated with early adoption that vary by national context.

Our analysis reveals that these aggregate patterns mask substantial income-based disparities. Higher-income households consistently spend more on energy in absolute terms than lower-income households (bottom decile), though this represents a significantly smaller portion of their income (approximately 3-4 times lower as a percentage). This creates disproportionate energy burdens, with energy transition impacts 2-3 times more significant for lower-income families as a percentage of household resources, highlighting the need for targeted adoption policies that address energy affordability concerns.

Using household-level survey data to project decile-specific technology adoption rates and consumption, we find that the timing of adoption significantly influences both the magnitude and distribution of energy cost changes. The observed patterns indicate that policy interventions aimed at accelerating adoption must address affordability constraints for lower-income households to avoid widening the energy burden gap. Our modeling framework demonstrates that targeted approaches could help distribute benefits more equitably across income groups. These findings highlight the critical importance of policy design in shaping both the efficiency and distributional impacts of demand-side innovations as part of the low-carbon energy transition.

New Advances in Energy Demand Research: Novel Methodology for Estimating Structural Change Effects

Nuno Bento

DINÂMIA'CET-Iscte, Lisbon, Portugal

Version of 28/02/2025

Abstract

This paper presents a novel methodology for estimating structural change in energy demand analysis, addressing key limitations in existing decomposition approaches. The proposed method explicitly distinguishes between *within-item (interaction) effects*, which capture the combined influence of activity and intensity changes within a sector category, and *between-item (reallocation) effects*, which reflect shifts in the composition of energy consumption across sectors or technologies. Practical examples demonstrate its ease of use. By applying the methodology to two scenarios for energy demand in 2050 with sectoral and spatial resolution, we find contrasting structural effects in the Low Energy Demand (LED) and the IEA's Net Zero Emissions (NZE) scenarios. While LED exhibits notable structural effects (though similar to historical experiences between 1950 and 1980), these are largely offset in NZE by the reallocation effects. The findings have significant implications for energy policy, offering a more precise assessment of how changes at the global, sectoral, and sub-sectoral (category) levels shape overall energy demand and sustainability trends. More than just a theoretical refinement with enhanced granularity, this is a practical tool for improving emissions and energy consumption analysis and decision-making. This tool can also be applied to any analysis involving physical and monetary variables (e.g., environmental policy, economics, finance). Enhancing analytical capabilities and methodologies for energy demand helps address the persistent underrepresentation of the demand-side solutions in research and policy.

Keywords: energy consumption disaggregation; structural change; between-item effects; within-item effects; Logarithmic Mean Divisia Index (LMDI); energy models.

Large Dispersion in the Diffusion of Social Innovations

Fast Track co-leads: Gregory Nemet and Charlie Wilson

Core writing team: Nuno Bento, Simon De Stercke, Caroline Zimm

Contributors: Anne van Valkengoed, Annalisa Solis, Jingjing Zhang, Michelle Johnson-Wang, Dani Wu, Arnulf Gruebler, Hiroyoshi Iwata, Masahiro Sugiyama, Benigna Boza-Kiss, Leila Niamir, Frauke Wiese, George Carew, Vivien Fisch-Romito.

Abstract

Low energy demand futures consistent with Paris Agreement goals depend on the diffusion of social innovations. We define social innovations as those not primarily defined as being hardware or material artefacts, while recognizing that social and technological innovations are commonly interdependent. Do insights from technological innovations apply equally to social innovations? And are there comparable indicators for measuring change over time in relative advantage, cost, market share, and other innovation characteristics of social innovations given no standardized economic or physical metrics are available? We collect and standardize time series data characterizing the historical diffusion of a sample of 27 social innovations, spanning behavioral, business model, and institutional innovations with adopters ranging from households to firms and governments. We also compile time series data to measure a set of 20 additional indicators for each SI, for which we could find appropriate data, e.g. shared expectations, risk and uncertainty, choice variety. We fit logistic growth functions and linear functions to the time series allowing us to extract standardized measures of diffusion speed to compare across time series. We complement our time series data with categorical data on a further set of 4 indicators e.g., policy dependence, social signaling. Our cleaned dataset comprises 383 time series (ranging from 4-163 years) in both global North and South, richly characterizing the diffusion dynamics of a diverse set of social innovations relevant to low-carbon futures. We find: (1) there is wide variability in diffusion speeds within our sample of social innovations, with a median logistic growth parameter of 0.14; (2) business model innovations diffuse fastest followed by institutional and then behavioral innovations; (3) the distribution of growth rates for social innovations is similar to that for technological innovations; (4) short formative phases are weakly associated with faster diffusion in later phases; (5) tests of other determinants of diffusion speed were inconclusive; and (6) growth in early adopter regions was similar to that in later adopting regions. Each of these hypothesis tests requires further refinement and data cleaning. We complement the quantitative analysis with two case studies of important drivers: attitudinal change and early adopting cohorts. Our analysis shows that it is both possible and insightful to quantify the diffusion dynamics of social innovations and so emphasize their importance alongside low-carbon technological innovations for which both data and theory are more readily available.

Table of contents

1. Introduction 3
1.1. Aims, Objectives and Research Questions 3
1.2. Approach 4
2. Definitions and hypotheses 5
2.1. Definitions of social innovation 5
2.2. Determinants of social innovation diffusion 6
2.3. Hypotheses on diffusion speeds of social innovations 7
2.4. Indicators to measure variables necessary for hypothesis testing 9
3. Data 11
3.1. Social Innovations 11
3.2. Temporal and spatial scales 12
3.3. Dataset assembly 14
3.4. Descriptive statistics for SIs in early adopter regions 16
4. Analysis and hypothesis testing 20
4.1. Do SIs grow faster than technological innovations? No. 20
4.2. Formative phases 22
4.3. Determinants of diffusion speed 24
4.4. Knowledge spillovers 26
5. Case studies of SI development 27
5.1. Case 1: Attitudinal precursors to eating less meat 27
5.2. Case 2: Falling drivers' licenses rates among a subgroup 29
6. Conclusions 32
6.1. Dataset and descriptive statistics 32
6.2. Comparisons and hypothesis testing 33
6.3. Case studies on attitudes and subgroup cohorts 34
6.4. Further research 34
7. Acknowledgements 35
8. References 35

1. Introduction

Reducing energy demand can deliver Paris-consistent futures (Grubler et al., 2018), while improving human well-being (Wilson et al., 2023). Combining high wellbeing with low energy demand – High-with-Low (HwL) - relies on widespread diffusion of both technological and social innovations (Nemet and Greene, 2022; Wiedenhofer et al., 2024). Within HwL futures, social innovations – those that are not primarily characterized by material artefacts - are particularly important (Niamir et al., 2024). For example, reducing meat consumption is an important HwL strategy involving dietary changes in many countries particularly in the global North (Verain et al., 2024). Similar strategies emphasizing social, behavioral, business model and institutional changes are evident in HwL futures for heating, cooling, travelling, consuming. These 'social innovations' (SIs) diffuse *alongside* changes in technologies and infrastructures with which they are often co-dependent. Any future consistent with limiting warming to 1.5-2C represents a strong discontinuity from historical trends, raising questions of feasibility amid rapid transformation. This applies equally to novel carbon removal technologies which are not needed in HwL scenarios (Grubler et al., 2018) as it does to the social innovations which are an integral feature of HwL scenarios (Steg et al., 2022). The feasibility of High-with-Low (HwL) thus depends on the diffusion speed of social innovations. The HwL narrative also emphasizes the enabling potential of digitalization as a particular type of entwined social and technological innovation (Wilson et al., 2023).

1.1. Aims, Objectives and Research Questions

Our aim in this paper is to better understand the drivers and dynamics of social innovation diffusion by testing the applicability of established insights from studies of technological change. As examples, we know that technological innovations diffuse more rapidly: (1) if they have higher relative advantage as perceived by potential adopters; (2) if their cost or performance improves as a function of experience (learning-by-doing); (3) if knowledge spills over from early to later adopting market segments; and (4) if they have longer formative phases to prepare for market takeoff. We apply this framework to a set of innovations whose primary dynamics involve behavioral, business model, institutional and organizational change.

A premise of our paper is that we have good data and insights on the drivers and dynamics of technology diffusion, but we lack a similar evidence base on the speed and patterns through which social innovations emerge, take off, and become widely adopted, both through time and across space. Our objectives are:

- To build an empirical basis for explaining the diffusion of social innovations relevant to High-with-Low futures.
- To characterize the speed of social innovation diffusion in relation to key determining factors.
- To compare and contrast diffusion dynamics of social and technological innovations.
- To raise the profile of 'hard-to-model' social innovations relevant for climate and sustainability goals.

We have three main research questions:

1. How fast have HwL social innovations diffused historically?
2. What characteristics of HwL social innovations and their adoption contexts explain their diffusion speed?
3. To what extent do the determinants of adoption for technological innovations apply to social innovations?

By addressing these questions with a limited effort we aim to generate a proof concept to help guide and motivate the effort to a larger data collection and analysis project in the future.

1.2. Approach

Our overall approach is threefold. First, we design a systematic data collection framework to capture the determinants of social innovation diffusion. Second, we use our framework to synthesize available time series and other data on a diverse sample of social innovation relevant to HwL futures. Third, we analyze diffusion dynamics in the resulting dataset, testing hypotheses on diffusion speeds.

We collect and standardize time series data characterizing the historical diffusion of a sample of 27 social innovations. Our definition and examples of social innovations includes behavioral, business model, and institutional innovations with adopters ranging from households to firms and governments. Examples range from eating less meat or organic food, travelling long-distance by train rather than plane, downsizing living space, microfinance, environmental investing, climate protest, energy communities, digital skills, and e-government.

Our time series data includes measures of adoption in both absolute and relative terms for each innovation, distinguishing both early and late adopting countries, regions or cities.

We also compile time series data to measure a set of >20 additional indicators for which we could find appropriate data (e.g. shared expectations, risk & uncertainty, choice variety). This ranges from 2-12 additional indicators per innovation. We fit logistic growth functions and linear functions to the time series (subject to a range of fit criteria). This allows us to extract standardized measures of diffusion speed (e.g., the logistic slope parameter) to compare between time series.

We complement our time series data with categorical data on a further set of 4 indicators (e.g., policy dependence, social signaling). Our full dataset comprises well over 383 time series (over periods from 4-163 years) in both global North and South richly characterizing the diffusion dynamics of a diverse set of social innovations relevant to low-carbon futures.

In our hypothesis testing, we use groupwise difference testing, bivariate correlations, and other simple statistical methods to explore relationships between diffusion speeds, innovation characteristics, and adoption environments. Each relationship we test is based on a theoretical or empirical insight demonstrated for technological innovations.

2. Definitions and hypotheses

2.1. Definitions of social innovation

To arrive at a definition of social innovations for this project, we reviewed the literature that includes definitions of social innovations and grouped them into the three categories below. Our goal was to find a pragmatic definition that provides some clarity what should be included and what excluded in this study, with an eye to focusing on innovations that have received less attention to date (Wilson et al., 2012). We thus define 'social innovations' as *the improvement and adoption of novel practices not primarily defined as being hardware or material artefacts, while recognizing that social and technological innovations are commonly interdependent*. We also draw on the literature to assign three categories of social innovations: 1) behavioral, 2) business model, and 3) social and institutional (Geels, 2024). We include a longer discussion of the definitional literature, including quoted text of other definitions, in the Appendix.

Organizations and Social Relationships. These definitions address the idea that social innovations are new ideas that are often collaborative across industries/communities. Avelino et al (2019) broadly describes social innovations as "change in social relations, involving new ways of doing, organizing, knowing and framing" (Avelino et al., 2019). This is broad enough to read in a hardware component but can apply to changes in social behaviors without needing new technology. In the energy industry, social innovation is often defined as changes across the industry with the goal of reducing greenhouse gas emission on both the supply and demand sides of the market (Sovacool et al., 2023a). Industry changes, along with innovative social organizations and practices, new forms of governance, supportive policies and regulations, and new business models work together to contribute to the low-carbon energy transition (Khanna et al., 2023). Similarly, the Joint Research Centre of the European Commission writes that social innovation in the energy sector could satisfy human and societal needs while in parallel empowering vulnerable social groups alongside "cultivating civic traditions of trust, equity, and solidarity within and beyond the spatial context on which they occur" (Koukoufikis, 2021; Mikkonen et al., 2020).

Culture and Social Benefits. Bouchard defines SIs as a way of problem solving that allows for "opportunities for the development of new social relations and/or cultural orientations in a way that improves life quality and living standards in society" when incorporating a new practice or product (Bouchard, 2013). SI culture emphasizes the need for effective, efficient, and sustainable solutions when developing new ideas that address social problems or social needs. These solutions can be initiatives in the form of new products, service, initiatives, organizational models or approach to the delivery of public services. The scope of SIs spans from modest and incremental to systemic and fundamental but share the same goal of moving towards a low carbon society (Nesta et al., 2014). Co-operation with local policymakers and municipalities is important to embed SIs into a community. Soft skills like communication and marketing abilities, and the capacity to cooperate and work together and technical, economic, and juridical skills have been in high demand. In affected communities, these skills are often provided by volunteers.

Social Behavior Based. The main driver of change comes from the people themselves as they adjust or adopt "sustainability-oriented changes in lifestyles and social practices" (Geels, 2024). Examples of communities and institutions that center social innovation include transition towns, eco-villages, family farming, social entrepreneurship, slow food, time banks, ethical banks, and degrowth. Along with sustainability, SIs strive to create social value by promoting social change, the development, and the empowerment of the community to encourage socially fairer and more inclusive results from new practices (Dall-Orsoletta et al., 2022). Social networks and social processes create important opportunities for societal development and help make societies more sustainable, cohesive and resilient through inclusive practices, coproduction and grassroots initiatives (Grimm et al., 2013). The Bureau of European Policy Advisors defines SIs as "innovations that are social in both their ends and in their means," placing the emphasis on the community's motivation to make sustainable lifestyle changes (2010) . It is important to note that these definitions do not acknowledge any advancements made by change in technology or infrastructure.

2.2. Determinants of social innovation diffusion

In earlier work we identified distinct characteristics of HwL innovation: 1) multiple attributes and new services; 2) many heterogeneous adopters; 3) peer effects, network effects; 4) granularity - small scale or modularity; 5) many iterations in learning cycles; 6) local system integration; and 7) rebound effects. We also conducted case study analysis on how quickly HwL innovations could be adopted using the examples of additive manufacturing, shared mobility, and solar prosumers (Niamir et al., 2024).

In addition to these characteristics of HwL innovations specifically, the large literature on technological change provides robust insights on the determinants or influences on adoption and resulting diffusion. We cluster these into four categories: formative phases, early adoption, diffusion accelerators, innovation dynamics (Table 1). These categories describe the innovation lifecycle from emergence to widespread diffusion (saturation and substitution is not covered here). Each of the determinants of technological innovation diffusion applies by analogy to social innovations (also shown in Table 1).

Table 1. Hypothesized determinants for the diffusion of social innovations.

	Technological innovations	**Social innovations**
Formative phases	•experimentation •RD&D projects & funding •alignment with infrastructure •protected niches	•experimentation •VC or risk finance •alignment with institutions •protected niches
Early adoption	•technical uncertainty & risk	•social uncertainty & risk
Diffusion accelerators	•technological learning •alignment with tech infrastructure •granularity (unit cost, unit scale, modularity)	•social learning •alignment with social norms & expectations •granularity (divisibility, number of actors involved)
Innovation dynamics	•cost reductions •performance improvements	•more choice availability •more convenience

2.3. Hypotheses on diffusion speeds of social innovations

From the diffusion determinants summarized in Table 1, we derive a set of simple hypotheses (H:) relevant to our interest in social innovations. As a simple example capturing the well-established finding on compatibility (innovation adoption) and norm compliance (social psychology), our expectation is that: Social innovations that align with social norms diffuse faster.

Each of our hypotheses is a simple bivariate relationship between an outcome variable – diffusion speed – and an explanatory variable – derived from literature. This bivariate relationship is under *ceteris paribus* conditions, i.e., all else being equal. Establishing simple associations between diffusion determinants and speeds is a first step towards more complex multivariate models.

Here we set out and justify a set of hypotheses that we test using our dataset on social innovations. This is a subset of a broader landscape of diffusion determinants.

H1: Social innovations with longer formative phases diffuse faster.

Formative phases describe the period before takeoff during which supportive institutional conditions develop to enable subsequent diffusion. *Ceteris paribus*, social innovations with longer formative phases should diffuse faster by allowing more time to reduce social risk and uncertainty, create a stronger enabling environment, align institutions and infrastructures, and so on. However, the converse is possible if longer formative phases are associated with social innovations 'failing' to diffuse beyond niches with highly specialized preferences.

H2: Social innovations with higher ease of use or accessibility diffuse faster.

H3: Social innovations with higher social visibility diffuse faster.

H4: Social innovations that deviate less from prevailing norms diffuse faster.

H2, H3 and H4 test three of the five innovation attributes identified by (Rogers, 2003) as explaining adoption rates: ease of use, observability, and compatibility. In each case the attributes are as perceived by potential adopters. The other two attributes are relative advantage and trialability which we include in our list of indicators and test elsewhere.

Ease of use (H2) is the inverse of complexity and captures whether potential adopters perceive skill, competence, or knowledge barriers to adoption. *Ceteris paribus*, less complex innovations are adopted more readily. For our social innovations we extend this to include ease of access or accessibility to capture whether potential adopters perceive high transaction costs to adoption e.g., if an innovation is not widely available across spatial scales.

Social visibility (H3) is analogous to Rogers' observability attribute. It has both physical and social meanings: is the innovation literally visible (e.g., clearly identifiable, observable, and used in public spaces) and is the innovation socially visible (e.g. talked about, commented on, judged, salient). Visibility serves to normalize innovations, increase the flow of social information in social

networks, and so reduce perceived social risks to adoption. *Ceteris paribus*, more visible innovations are adopted more readily. An additional dimension of social visibility is salience. Salient social innovations are more memorable, topical, or otherwise stand out, so are more likely to be the subject of interpersonal information exchange in social networks. These peer influences are an important characteristic of social innovation diffusion (see earlier).

Deviation from prevailing norms (H4) relates to Rogers' compatibility attribute which measures both compatibility with values and other cognitions, and compatibility with lifestyles and daily routines. Compatibility reduces the transaction cost of time, effort, or intention formation associated with switching from an existing practice to the social innovation. *Ceteris paribus*, more compatible innovations are adopted more readily. However, for our social innovations, deviation from the norm also has a wider social dimension: to what extent does the innovation challenge prevailing collective norms or expectations? The larger the deviation, the higher the social risk of adoption (norm non-compliance) and so the more likely adoption is confined for longer in specific early adopting niches (e.g., foregoing driving licenses among teenagers in cities well served by public transport).

H5: Social innovations adopted initially in protected niches diffuse faster.

Protected niches (H5) for technological innovations typically offer cost- and performance-insensitive adoption by very specific types of early adopters who are either novelty-seeking or who have strong preferences for specific performance requirements. Canonical examples for solar PV include NASA for deployment on satellites or the US military for deployment on remote bases. In both cases the distributed, renewable characteristics of power generation outweighed high upfront costs (in the early decades of PV's innovation lifecycle). *Ceteris paribus*, innovations with protected niches are adopted more readily – at least by an initial tranche of innovators. This stimulates learning and improvement cycles that make the innovation more appealing for those outside the niches. For our social innovations, cost and performance attributes are not always as meaningful as they are for technological innovations. However, in some cases, specific adopters are clearly identifiable as having strong value-based propensities towards adoption despite potentially high social risks (norm deviation).

H6: Social innovations with enabling policy environments diffuse faster.

Enabling policy environments (H6) can take many forms including policy measures, legislation, incentives (financial or otherwise), standards, regulatory frameworks. They may be identifiable in the positive (incentives) or in the negative (absence of barriers). *Ceteris paribus*, innovations with more supportive policy contexts are adopted more readily.

H7: Social innovations adopted by individuals diffuse faster.

Adopters of our social innovations (H7) range from individuals and households (adopter 'size' = 1-10) to firms, organizations or collectives (adopter 'size' = 1->1000). Individual adopters have lower internal decision-making constraints on adoption; but unlike collectives or organizations they may

also be less able to exert influence on adoption contexts to facilitate adoption. Consequently, we do not have clear expectations for this hypothesis. In our testing we frame it around individual adopters as these represent a more 'granular' adoption process involving fewer people. Ceteris paribus, innovations adopted by discrete individuals are adopted more readily.

H8: Social innovations diffuse faster in later adopting regions.

Early adopting regions generate knowledge on how to effectively improve or use innovations including through enabling changes in the adoption context (e.g., removing regulatory barriers, ensuring access to infrastructure). Knowledge spillovers (H8) describe how this learning experience can benefit later adopters as the innovation diffuses spatially out of its early adopting region. As innovations diffuse from core to rim and periphery, diffusion speeds accelerate … even though diffusion extents (market penetration or saturation levels) tend to lower. Arnulf Grubler calls this Schmidt's Law (Grubler, 1990).

2.4. Indicators to measure variables necessary for hypothesis testing

To test hypotheses from the literature on the determinants of diffusion speed (Table 1), we require data on relevant explanatory variables as well as on diffusion speed as our outcome variable. For the subset of hypotheses expanded on in the previous section, the explanatory variables are clearly set out in each hypothesis. To measure these variables, we established a long list of indicators to structure our data collection. These indicators are of four types: (1) measures of adoption over time - our main outcome variable; (2) measures of innovation characteristics, (3) measures of adoption contexts, and (4) hybrid measures of innovation characteristics and adoption contexts – our different explanatory variables.

This long list comprised 33 indicators from which we selected 23 as a 'priority list' for our initial wave of data collection. Table 2 lists all the indicators and summarizes the total number of time series data collected per indicator. We have 27 social innovations in our sample (see next section), but for some indicators we collected >>1 time series per innovation. This is for two reasons. First, we have >1 spatial scale of analysis (e.g., early and later adopting countries). Second, each indicator can be measured by different possible metrics. Taking '1.1 Adoption over Time' as an example, metrics of adoption can be expressed in relative terms (% share of adopter population) or in absolute terms (total numbers). For indicators like '2.1 Learning', for technological innovations, metrics have been standardized as $/MW (cost) or as % efficiency (performance). There are no equivalent standardized metrics for social innovations. Given the novelty of our indicator definition in the social innovation field, to help guide our search for metrics we defined each indicator with a guiding question and examples – these are provided in the Appendix.

Table 2. Priority list of indicators to measure diffusion variables.

#	Indicator	Description of Indicator	Number of social innovations with available time series data	Total number of time series
1.1	Adoption over time	adoption or use (diffusion curve) **	27	503
1.2	Formative phase	initial (slow) phase of adoption	0	0
2.1	Learning	cost	3	5
2.2	Relative advantage	profitability	5	22
2.3	Relative advantage	co-benefits (non-monetary)	3	9
2.4	Ease of use	ease of use, accessibility	3	26
2.5	Variety	choice availability	6	48
2.6	Visibility	social signaling, identity or status-linked	0	0
2.7	Granularity	adopter/user 'unit size'	1	3
2.8	(Perceived) uncertainty & risk	trialability	0	0
2.9	Inter-dependence (with hardware)	link to physical artefact	8	23
2.10	Inter-dependence (with hardware) - unit size	unit size of linked physical artefact	3	2
3.1	Adopter type	adopter 'unit' (e.g., individual, firm)	0	0
3.2	Adopter characteristics	sociodemographic	7	79
3.3	(Perceived) uncertainty & risk	knowledge generation	26	26
3.4	(Perceived) uncertainty & risk	protected niches	0	0
3.5	Market formation	entrepreneurial activity	10	807
3.6	Market formation	policy support	0	0
4.1	Knowledge flows	salience	26	152
4.2	Knowledge flows	mass media	5	16
4.3	Compatibility	extent of deviation from norm	3	10
4.4	Provisioning system	(social) infrastructure size	1	2
4.5	Infrastructure dependence	physical infrastructure dependence	9	35
4.6	Standardisation	rules, standards, quality assurance	0	0

Notes:
for indicators denote type : 1 = diffusion over time and space; 2 = innovation characteristics; 3 = adoption contexts; 4 = innovation characteristics + adoption contexts
** diffusion measured at different spatial scales or 'adoption niches' relevant for the innovation (e.g., early-adopting social group -> city -> country)

3. Data

3.1. Social Innovations

We initially identified a set of 34 social innovations that: (1) are consistent with a HwL scenario; (2) fit our conceptualization of social innovations; (3) span innovation types. We dropped 6 innovations due to data accessibility constraints. These were: one-stop shops for building retrofits, ESCOs (energy service companies), shared pooled mobility, balcony solar, climate literacy, climate policy support. Our final sample comprised 27 social innovations (Table 3). Although many are still at an early lifecycle stage (e.g., e-bikes), some date back decades (e.g., firm ESG reporting), and others longer (e.g., eating less meat).

Table 3. Our sample of 27 social innovations of different types.

Innovation Name	Label	Type	Typical Adopter
eating less meat	eat	behavioural	individual or household
organic food consumption	org	behavioural	individual or household
mobesity (car size) *	crz	behavioural	individual or household
long-distance rail travel	low	behavioural	individual or household
car ownership	cro	behavioural	individual or household
teleworking	tel	behavioural	individual or household
active mobility	act	behavioural	individual or household
e-bikes	ebi	behavioural	individual or household
drivers licence	dri	behavioural	individual or household
downsizing	dow	behavioural	individual or household
co-housing	coh	behavioural	individual or household
sustainable fashion	sus	business model	household or firm
food waste reduction	foo	business model	household or firm
e-commerce	eco	business model	household or firm
passive building retrofits	pas	business model	household or firm
car sharing	crs	business model	household or firm
microfinance	mic	business model	household or firm
solar leasing	sol	business model	household or firm
firm ESG reporting ^	fir	business model	household or firm
textile recycling	tex	business model	household or firm
digital skills	dig	institutional	collective or system
e-government	ego	institutional	collective or system
climate protest *	cli	institutional	collective or system
energy community	ene	institutional	collective or system
non-cash transactions	non	institutional	collective or system
quitting smoking +	qui	institutional	collective or system
postage stamps +	pos	institutional	collective or system

NOTES
^ ESG = environmental, social, governance
* dropped from final analysis due to data reliability concerns
+ only indirectly LED-related

3.2. Temporal and spatial scales

For each social innovation, we identified metrics of adoption over time in both relative terms (e.g., market shares) and absolute terms (e.g., total numbers). We targeted a minimum duration of 10 years to ensure the data covered a reasonable part of the adoption lifecycle, though in a few cases we relaxed this constraint due to data constraints.

For each social innovation, we compiled at least 1 adoption time series. Average duration was 27.4 years, with a range of 4-163 years (see Table 4).

For each social innovation, we identified a city, country or region associated with early adoption, subject to data availability. In most cases these data constraints meant we selected countries as our early adopting spatial scale. However, in some cases we were able to identify more specific early adopting niches within cities or countries: e.g., for driving licenses, we selected <19 year olds in Stockholm and Washington DC. In cases for which early adopting countries were not clearly known *ex ante*, we collected adoption data from multiple countries and assigned as early adopter the country with the earliest takeoff point. In one case we could only source global data so assigned this as our early adopting spatial scale. The average number of spatial scales per innovation was 3.3, with a range of 1-8 (see Table 4).

Table 4. Temporal & Spatial Scales of our Social Innovation Data.

Innovation Name	Label	Temporal Scale: Adoption over Time (yrs)	Spatial Scale: Number of Regions	Spatial Scale: Early Adopting Region	Spatial Scale: Other Regions
eating less meat	eat	52	5	Germany	India,Japan,UK,US
organic food consumption	org	19	6	Denmark	Austria,Canada,Japan,Switzerland,UK
mobesity (car size) *	crz	22	2	France	Germany
long-distance rail travel	low	26	1	Germany	-
car ownership	cro	32	3	Heidelberg	Berlin,Hamburg
teleworking	tel	6	8	The Netherlands	The Netherlands
active mobility	act	18	4	The Netherlands	The Netherlands
e-bikes	ebi	8	3	The Netherlands	The Netherlands
drivers licence	dri	29	4	Stockholm	Sweden,Washington DC, US
downsizing	dow	5	1	Switzerland	-
co-housing	coh	45	3	Denmark	Germany,US
sustainable fashion	sus	12	1	Global	-
food waste reduction	foo	12	1	United States	-
e-commerce	eco	24	5	United States	China,Germany,South Korea,UK
passive building retrofits	pas	26	3	Germany	Austria,Belgium
car sharing	crs	27	1	Germany	-
microfinance	mic	20	3	India	Bangladesh,Nigeria
solar leasing	sol	13	5	New Jersey	California,Connecticut,Massachusetts,US
firm ESG reporting ^	fir	18	1	Europe	-
textile recycling	tex	49	1	United States	-
digital skills	dig	22	6	Sweden	Denmark,Italy,Norway,Poland,Portugal
e-government	ego	16	6	Sweden	Estonia,Hungary,Latvia,Portugal,UK
climate protest *	cli	4	7	Sweden	Bangladesh,Germany,Global,India,UK,US
energy community	ene	38	1	The Netherlands	-
non-cash transactions	non	14	3	Sweden	UK,US
quitting smoking +	qui	21	5	UK	Brazil,China,India,US
postage stamps +	pos	163	1	UK	-

NOTES
^ ESG = environmental, social, governance
* dropped from final analysis due to data reliability concerns
+ only indirectly LED-related

3.3. Dataset assembly

Our data collection process involved a large team of researchers working in parallel to identify and compile available data on specific innovations, using a standardized data template defining the priority list of indicators (Table 2). For each innovation, we collected time series data for our main adoption indicator (1.1 Adoption over Time) and as many other indicators as possible subject to data constraints. If time series data were not available, we recorded qualitative information for each indicator for use in coding categorical variables (e.g., yes/no dummies – see below).

On completion, we then checked, cleaned, harmonized to ensure comparability, and then synthesized all the innovation datasets into a single master dataset. We gave each time series a unique label with five elements based on meta data: (1) innovation name; (2) spatial scale; (3) indicator number; (4) description; (5) metric.

We transformed select time series to ensure comparability and consistency with our research aims:

- *Normalization* of absolute measures of diffusion (a measure of indicator 1.1 Adoption over Time) to create relative measures of 'market share' over the scale 0-100%. Example: # of people using e-government services transformed into % population using e-government services.
- *Cumulative* totals of volatile annual time series to create measures of accumulating stock. Example: # of new start up companies per year (a measure of indicator 3.5 Market Formation) transformed into cumulative # of start ups over time.
- *Division* of time series if trend reversals meant only part of the time series captured the period of interest. Example: eating less meat in Germany (grams red meat per person per year) increased from 1972-1986, then declined 1987-2020; a partial time series was created just for this latter period.

For each time series we then tested the fit of logistic growth, exponential, and linear functions. Logistic growth models (S-curves) are the standard functional forms for innovation diffusion comprising three parameters: slope (b), inflection point (t_0), and asymptote (K). For time series not yet reaching an inflection point (when growth starts to slow), logistic growth and exponential functions are hard to distinguish. Linear functions were used only as a basic trend line (as few of our time series were obviously linear).

We used multiple exclusion criteria to select appropriate fits. For logistic growth functions, our inclusion criteria were:

- Criteria 1 *Goodness of Fit*: $R^2 < 0.70$
- Criteria 2 *Duration*: <5 non-zero data points (or <10 year duration)
- Criteria 3 *Missing Data*: <90% of data points are non-zero
- Criteria 4 *Discontinuities*: Year-to-year change in values of <-80% or >250%
- Criteria 5 *Volatility*: Autocorrelation (lag 1) threshold <0.70

- Criteria 6 *Lifecyle Coverage*: <40% of asymptote K covered in data series

We used additional visual inspection of fits on the borderline of one of more of these exclusion criteria to identify and screen out poor fits. For linear functions, our exclusion criteria were R^2 < 0.30 and the same lifecycle coverage criteria as for logistic growth functions.

This process of cleaning, transforming, and selecting useable time series yielded a full dataset of 1,768 time series. As noted earlier, this included multiple time series using different data sources and metrics to describe the same indicator for the same innovation.

To make our initial analysis more tractable, two researchers independently selected the preferred metric for each unique innovation – indicator pair. We then discussed and resolved differences for a final consensus set of preferred time series for diffusion speed (indicator 1.1 Adoption over Time), and for all our explanatory variables (indicators 3.1, 3.2, etc.) for which we had time series data. We distinguished these time series just for the early adopting region for each innovation, and again for all regions. Identifying only early adopting regions per innovation ensures comparability when comparing across innovations and adoption contexts.

The final sets of preferred time series used in our analysis in each of these categories is summarized in Table 5. For the main diffusion speed indicator 1.1, we had 27 time series for early adopting regions, one per innovation in our sample. However, when screening out poorly fitting logistic functions, this reduced to 24 time series.

Table 5. Time series with screened useable model parameters from logistic growth functions (logfits) and linear functions (linfits).

# TIME SERIES	total count	useable logfits *	useable linfits	spatial scale
1.1 Adoption over Time	27	24	27	early adopting (EA) region only
1.1 Adoption over Time	90	77	89	all regions
all other indicators (not 1.1)	92	77	85	early adopting (EA) region only
all other indicators (not 1.1)	283	236	262	all regions

Notes: * 3 innovations dropped due to poor fits: low-carbon long-distance travel; passive building retrofits, teleworking.

When using slope parameters from logistic growth or linear functions to compare diffusion speeds across innovations, we reversed the sign of the slopes for those innovations for which HwL-consistent diffusion is downwards not upwards. For example, a negative growth rate for our 'eating less meat' innovation using the metric 'red meat as a % of all meat consumption' is HwL consistent. We kept the absolute value of this growth rate but with a positive sign when pooling it with other HwL innovations. This sign reversal procedure applied to measures of food waste, meat consumption, car ownership, driver's licenses, and smoking. In each case downwards trends are HwL consistent with the corresponding innovation defined as food waste reduction, eating less meat, foregoing car ownership, not applying for a driver's license, and quitting smoking.

In addition to these time series data described by logistic growth and/or linear functions, we used qualitative data to code dummy variables (e.g., deviation from social norm – yes/no). Six members of the research team independently coded all 27 social innovations against six indicators for which no time series data were available. We then discussed and resolved differences for a final consensus set of codes. These are used for comparing groups of innovation in our hypothesis testing (see below).

Once these results are published, we will make the full cleaned data set publicly available as the Diffusion of Social Innovations (DOSI) data set.

3.4. Descriptive statistics for SIs in early adopter regions

The resulting data set provides information on several social innovations spanning behavioral, institutional and business model innovations. Here we provide a first look at the data across these social innovations. To show the outcomes of the curve fitting described above, Figure 1 shows the data points themselves, as dots, for 23 SIs that meet our exclusion criteria. The data shown are for the early adopting region. That figure of 23 panels also includes fitted curves for each SIs: linear in green, exponential in red, and our preferred measure of growth, logistic in blue. We focus on the preferred diffusion metric in each, market share. These panels clearly show the variation in data across SIs, including, data length, goodness of fit, and rate of change. For example, the panel in the top left shows active mobility in the Netherlands, which is of moderate length, generally slow but steady growth, and high goodness of fit. Because the growth is slow and the data are set in the middle of the growth period, all three functional forms are similar in both fit and in magnitude of growth. As another example, the panel on bottom right, textile recycling in the US has a shorter series, slightly poorer fit, but covers more of the range between asymptotes of the logistic function. These panels are 23 of the broader set of 1600 fits to data we analyze in this project. These data and the fits to them provide the basis for analyses of growth patterns and the drivers of them.

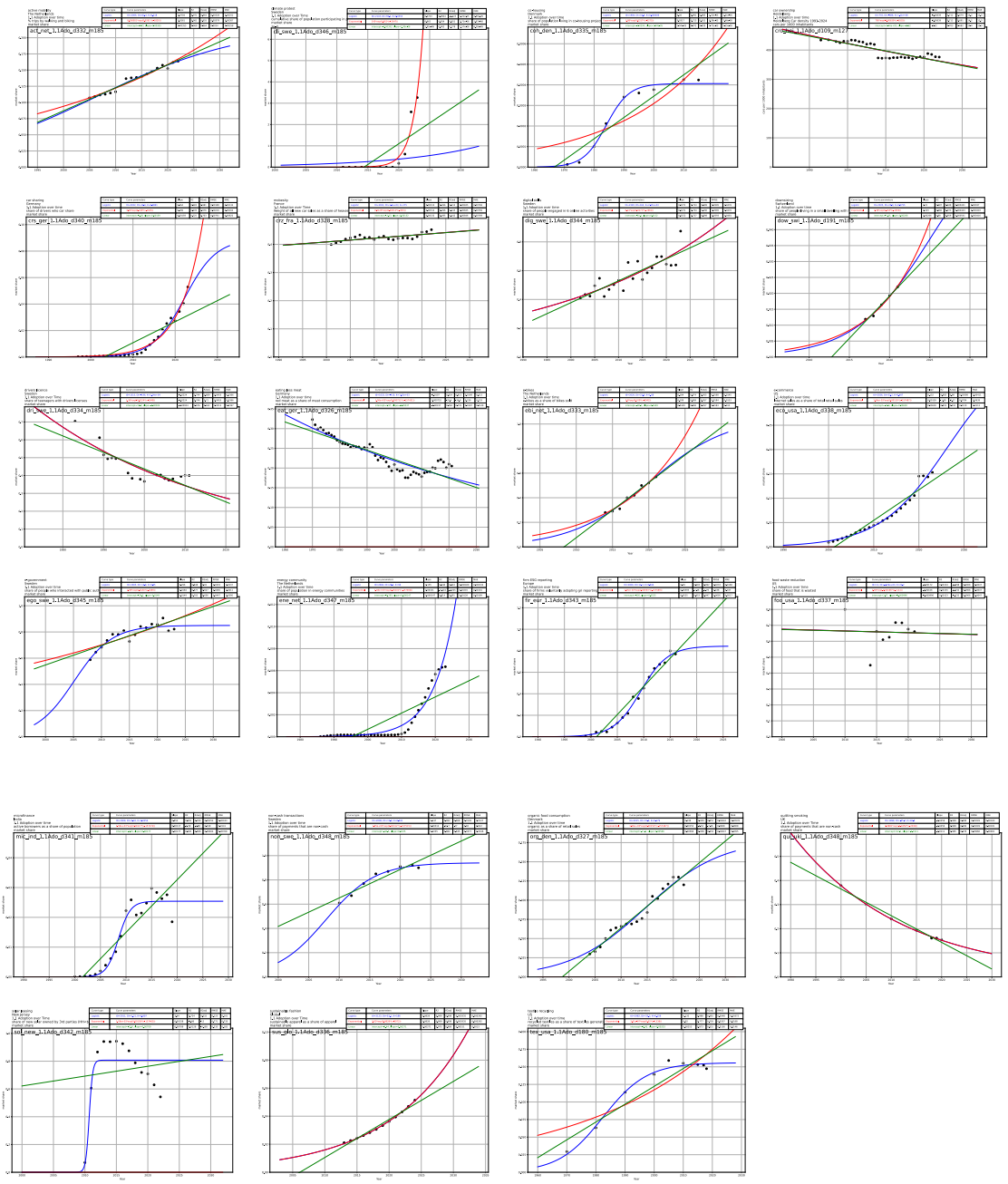


Figure 1. Main indicators of diffusion. Logistic, linear, and exponential fits to data for 23 social innovations.

As discussed above, the logistic parameter is our preferred metric because it is well aligned with theory of diffusion. We thus focus our analysis on the growth parameter in the logistic function and compare them across SIs in early adopting regions (Figure 2). That histogram shows a mode in the lowest bin, a median at 0.14, and a range that extends to well over 1.

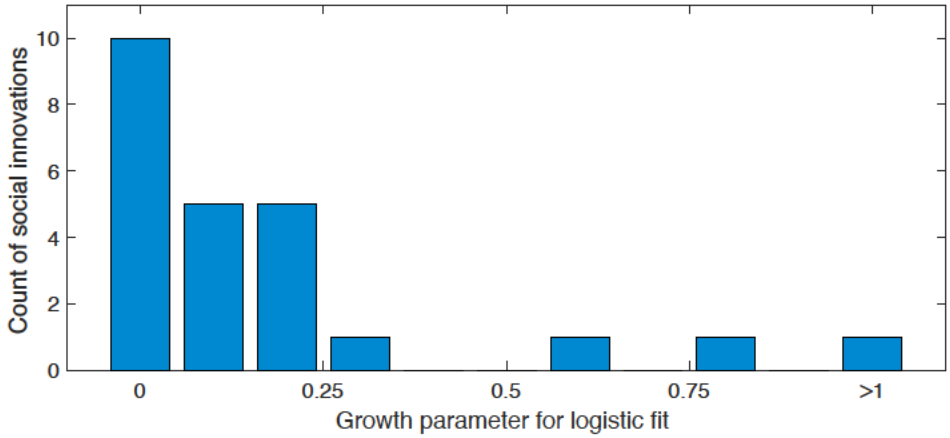


Figure 2. Histogram of logistic growth parameters for 24 social innovations in the early adopting region for each.

We conduct diagnostics on these data to understand their distributions as well as correlations among them. In Figure 3, on the left panel we assess whether goodness of fit has a relationship with the growth rate and find only a weak relationship. This result is fairly encouraging in that it suggests that lower goodness of fits do not bias the results on growth, indicating that we can obtain growth rates from data that do not perfectly fit a logistic function. In the right panel we plot the growth rate against the extent of the data set across the diffusion process. Our metric, data range divided by the asymptote on the logistic function is meant to assess how much of the diffusion process our data span. We see wide variation in that metric, albeit with several SIs spanning only a small range of the data. There is a relationship between range and fit in that we see higher growth for SIs for which our data span a larger portion of the diffusion process.

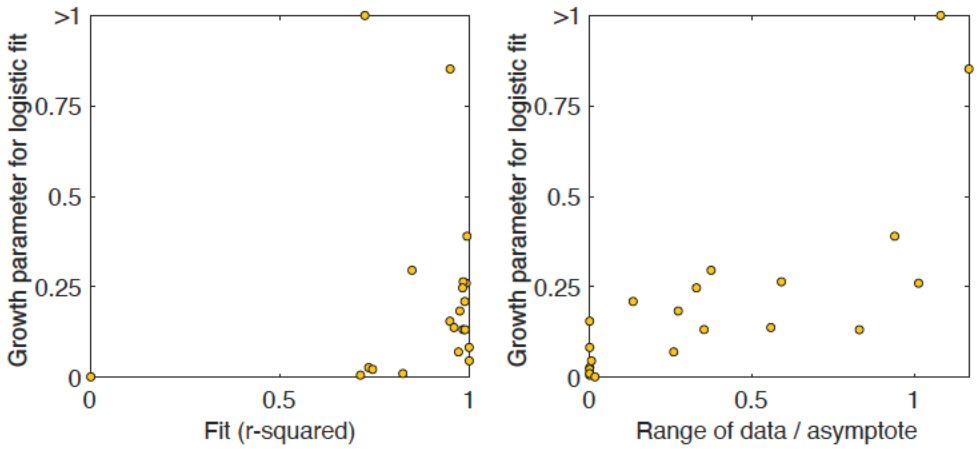


Figure 3. Logistic fit parameters for diffusion data compared to goodness of fit (left) and range of data as a proportion of asymptote of logistic curve (right).

In Figure 4 we compare the linear growth rates to the logistic ones to assess how well correlated one is with the others. This comparison is important because for some SIs the logistic fits are poor and it would be useful to know whether linear fits could serve as a proxy for logistic. We plot logistic against linear in the left panel and find a positive slope (i.e. there is some correlation) but with low goodness of fit. Note that because some growth rates are outliers, the actual curve is above the range plotted here, which is limited to 0-0.6 to show dispersion among data in that range. How we handle outliers will be important in subsequent work. One way to handle outliers is to use non-parametric measures. In the right panel, we drop the values of growth rates and focus simply on their rank among SIs. Again, we see a positive slope, but poor fit. We should thus exercise caution in using linear growth rates in lieu of logistic ones.

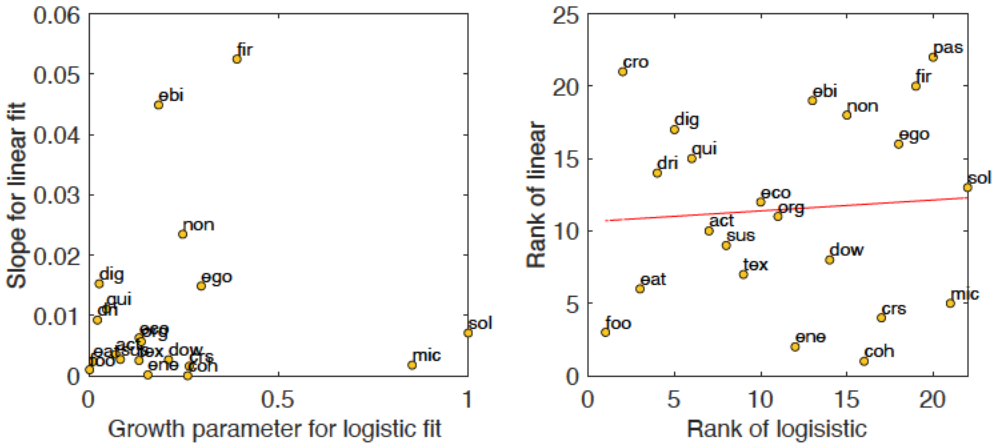


Figure 4. Correlation between log slope and linear slope for innovations with useable fits for both in 1.1 (n=22). Left panel compares parameter values and right panel compares rank in parameter values.

Finally, we look at different categories of SIs as well as how the early adopter regions, on which we have focused so far in this section, compared to all regions. In Figure 5, we compare categories and regions. In the left panel, we use the same data as in previous analyses in this section, focusing on market share growth in early adopter regions. We see that the median for behavioral innovations (0.104) is lowest and that for institutional (0.155) is 50% higher. The median for business model innovations (0.264) is more than double behavioral, albeit not significantly so. We see a similar pattern when adding later adopter regions with medians for behavioral (0.064), intuitional (0.075), and business model (0.295) having the same rank. The theory of knowledge spillovers suggests that growth in follower regions should be faster than that in early adopter regions. Here we see that holds for business model innovations, but not for behavioral and institutional innovations. It could be that the factors that hold back these regions from becoming early adopters in the formative phase persist in later phases and outweigh knowledge spillovers, and further that this persistence exists for behavioral and institutional but not for business model innovations.

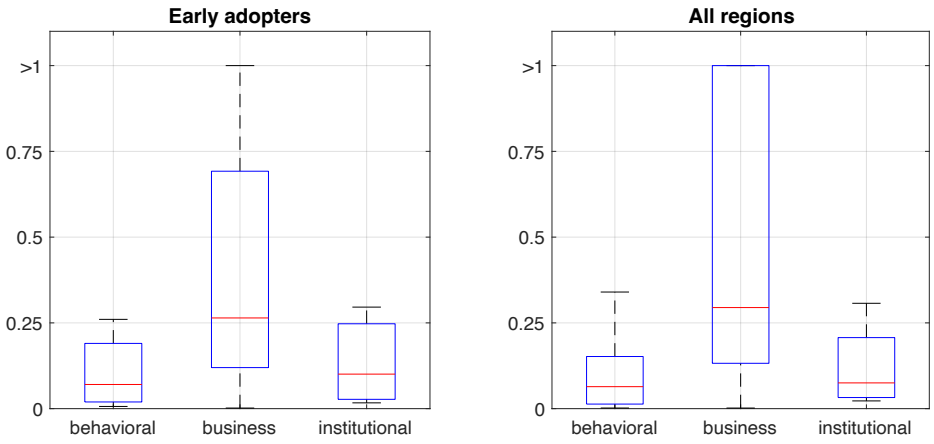


Figure 5. Growth rates distribution by social innovation category. On left: early adopter country, 1 per innovation. On right: all regions.

4. Analysis and hypothesis testing

We analyze these data to address our main research questions in the sections below. We first compare growth in social innovations to that of technological innovations, then we assess dynamics during social innovations' formative phases and finally we test hypothesis related to the determinants of diffusion speed for social innovations.

4.1. Do SIs grow faster than technological innovations? No.

One persistent question at the core of debates about energy transitions is whether social innovations tend to be adopted more quickly or less quickly than technological innovations (TIs). The argument for fast SIs is that technological shifts entail long formative phases, emergence of complementary innovations, necessary infrastructure, and overcoming risk-aversion in early periods (Grubler et al., 1999). In contrast, SIs can occur nearly instantaneously at the level of the individual and powerful forces such as peer effects can catalyze their adoption (Dietz et al., 2009). The opposite hypothesis would be based on arguments that SIs depend heavily on culture and norms, which are much more resistant to change (Rayner and Malone, 1997) and also that behavioral changes are ephemeral and thus appear quite limited when looking at larger spatial and temporal scale (Allcott and Rogers, 2014). Of course, as discussed in our definitional section above. all innovations involve both a social component and technological components. The distinction we make here between SIs and Tis is on an assessment of the core innovative features.

We thus compare diffusion rates among our set of social innovations to an analogous dataset on the diffusion of technological innovations. The Historical Adoption of TeCHnology (HATCH) data set includes time series data on over 200 technologies (Nemet et al., 2023a). The HATCH dataset spans a wide array of technologies across different regional scales and time periods. This includes, for example, data on small, digital technologies such as cell phones as well as large, industrial technologies such as railroads. The data are all made available online and includes periodic updates such as additional countries, more recent data, additional technologies, and

characteristics of each series (Nemet et al., 2023b). For this analysis we obtain data from the first release of HATCH, which includes data for 147 technologies spanning 11 categories of technology. While latter version of HATCH include data on multiple countries for each innovation, we use the version 1.0 which includes a single measure for each technology, corresponding to the early adopter, largest adopter, or global data. This aligns with the early adopter among our social innovations data, although the correspondence may not be perfect.

In Figure 6 we make the comparison between the DOSI social innovation data and the HATCH technological innovation data. We use the same curve fitting for both and extract the steepness parameter for a logistic function fit to the data. One immediately sees the large dispersion in growth rates as seen above in Section 4 for DOSI, as well as for technological innovations as also observed in the literature (Nemet et al., 2023a). A second observation is how similar the distributions are, with the median for technological (0.150) just slightly higher than that for social innovations (0.147).

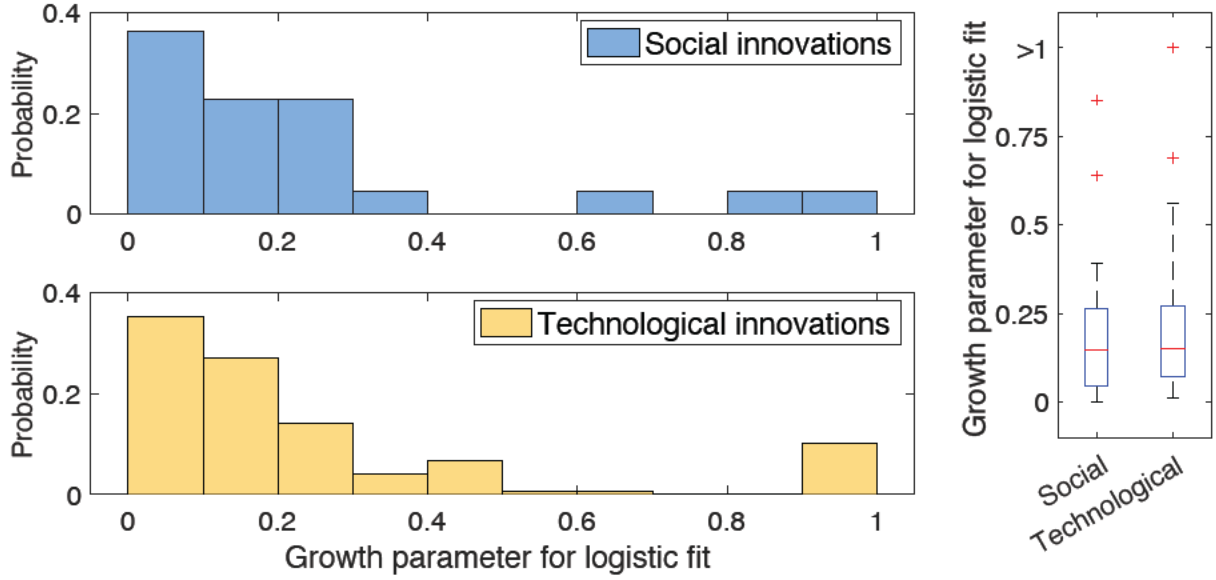


Figure 6. Comparison of logistic growth parameters for social innovations and technological innovations.

In Figure 7, we compare the technology categories within DOSI and HATCH. Pooling these 14 categories and comparing medians we find business model innovations at the 82nd percentile, institutional innovations at the 68th percentile and behavioral innovations at the 25th percentile. This further suggests that, for the early adopter regions we see here, the variation within categories as well as within social (and within technological) are larger than the differences between social and technological overall. We will be looking further into these relationships as we focus on aligning the two data sets and using the more recent version of HATCH.

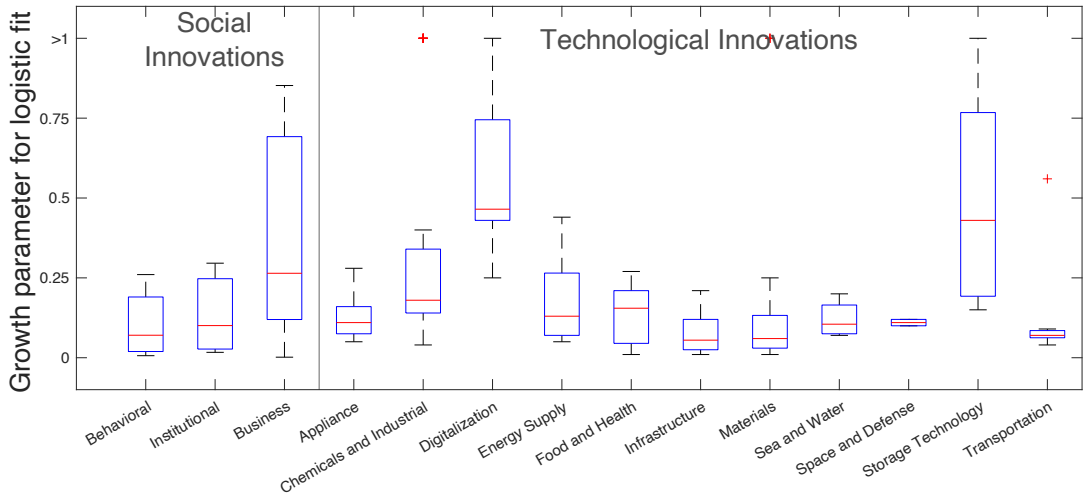


Figure 7. Comparison of logistic growth parameters for social innovations and technological innovations, by categories.

4.2. Formative phases

As noted earlier, formative phases describe the period before takeoff during which supportive institutional conditions develop to enable subsequent diffusion. Our expectation for social innovations is that longer formative phases should enable faster diffusion by allowing more time to reduce social risk and uncertainty, create a stronger enabling environment, align institutions and infrastructures, and so on.

H1: Social innovations with longer formative phases diffuse faster.

The average formative phase duration for technological innovations relevant to energy transitions is around two decades (Bento et al., 2018). The start date of the formative phase can be measured by the first 'commercial' appearance of an innovation (i.e., available for early adoption) which can be many years after its initial invention. The end date of the formative phase is not defined but can be proxied by a 2.5% market share which is the end of the risk-seeking 'innovators' adopter segment and the beginning of early adoption (Rogers, 2003). This yields a crude measure of formative phase duration (Bento and Wilson, 2016).

To test H5, we collected data to measure formative phase duration and examined the correlation with diffusion speed. Table 6 shows available data on formative phase duration for a subset of 8 social innovations in our sample.

Table 6. Formative Phase Durations for 8 Social Innovations.

Innovation Name	Label	Spatial Scale	Formative Phase Start	End	Duration (yrs)
car sharing	crs	Germany	1997	2016	19
e-bikes	ebi	The Netherlands	1997	2004	7
e-commerce	eco	US	1994	2006	12
e-government	ego	Estonia	2002	2005	3
organic food consumption	org	Switzerland	2000	2003	3
microfinance	mic	Bangladesh	1974	2000	26
downsizing	dow	Switzerland	2000	2022	22
firm ESG reporting	fir	Global	1999	2006	7

Figure 8 plots the relationship between formative phase duration and diffusion speed, using the slope parameters from the logistic fits (left panel) and linear fits (right panel) for the early adopting region only. Although there is wide scatter, the correlation between formative phase duration and the logistic slope is positive. This is consistent with H5. However, this is not robust to measurement specification as the correlation reverses if linear slopes are used (right panel). In further work we plan to extend the analysis using a larger sample of innovations, and to control for the effect of variation in innovation characteristics including their type (behavioural, business model, institutional), their recency (e.g., year of inflection point), and other characteristics.

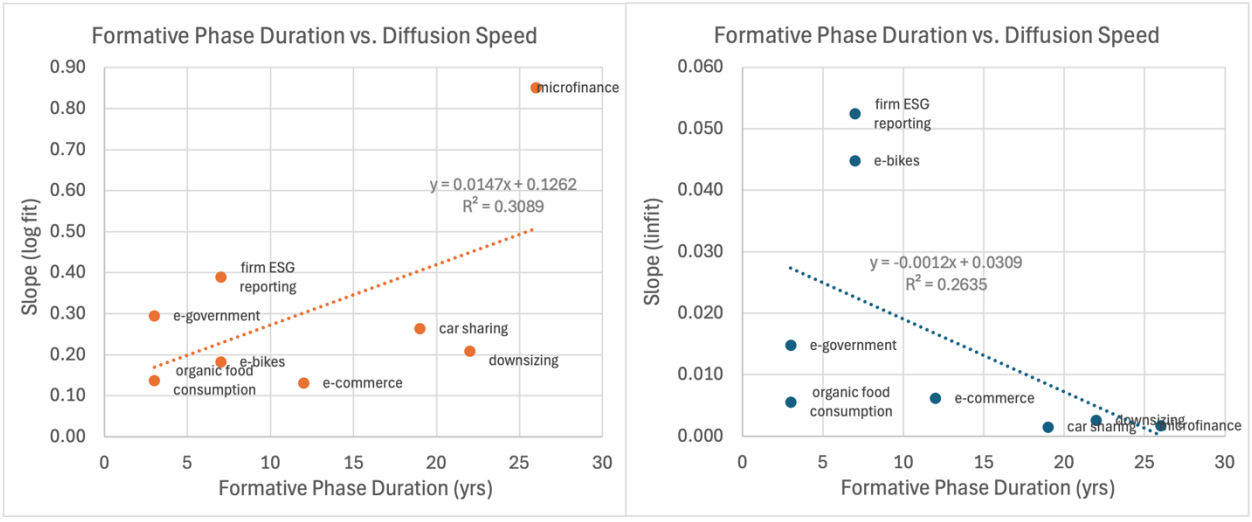


Figure 8. Formative Phase Durations vs. Diffusion Speeds. Notes: Diffusion speeds measured as slope parameters from logistic functions (left) and linear functions (right) fitted to adoption time series from each innovation's early adopting region.

4.3. Determinants of diffusion speed

Earlier we set out simple hypotheses on the determinants of diffusion speeds for social innovations, drawing on evidence from the technological change literature. Here we test specific hypotheses using groupwise comparisons (student t-tests, medians) of diffusion speeds measured both by logistic function and linear function slope parameters fitted to diffusion time series expressed as market shares.

H2: Social innovations with higher ease of use or accessibility diffuse faster.

H3: Social innovations with higher social visibility diffuse faster.

H4: Social innovations that deviate less from prevailing norms diffuse faster.

H5: Social innovations adopted initially in protected niches diffuse faster.

H6: Social innovations with enabling policy environments diffuse faster.

H7: Social innovations adopted by individuals diffuse faster.

For the explanatory variables in each of H2-7, we use yes/no dummies coded for each innovation by the research team based on available literature. For the explanatory variables in H7, we use categorical coding for each innovation to distinguish individual, household, firm, organization, collective as the main adopter type, then we reduce this to an individual/non-individual dummy.

As an example of our coding, we considered just under half of our social innovations to be strong deviations from prevailing norms. Examples include car sharing and foregoing car ownership in a strongly auto-mobility dependent culture; co-housing or downsizing living space in a strongly home ownership and space oriented culture. For social innovations that ultimately succeed in becoming widespread, what is initially a deviation from the norm becomes the norm if it substitutes for the incumbent.

Table 7 shows the groupwise comparisons testing H2-H7. Significant differences between groups are shown in red. As can be seen, there is almost no evidence to support any of the hypotheses whether diffusion speeds (in early adopting regions) are measured using the slope parameters of logistic or linear functions. The one exception (H4) is that social innovations coded as not deviating from prevailing norms show significantly faster linear diffusion. In one other case (H5), evidence is contrary to our hypothesis on social innovations with protected niches: these show slower linear diffusion.

Table 7. Testing hypotheses H2-H7 on diffusion speeds.

	2.4 Ease of Use			2.6 Salience/Visibility			4.3 Deviation from Norm		
TESTS USING LOGISTIC FUNCTION SLOPES		2.4=YES	2.4=NO		2.6=YES	2.6=NO		4.3=YES	4.3=NO
	count	14	5	count	11	8	count	6	13
	mean	0.447	0.171	mean	0.200	0.614	mean	0.163	0.472
	stdev	0.757	0.099	stdev	0.194	0.753	stdev	0.088	0.760
	median	0.161	0.155	median	0.138	0.229	median	0.183	0.138
	t-test	0.307	ns	t-test	0.375	ns	t-test	0.281	ns
	H1: FASTER adoption if			H2: FASTER adoption if			H3: SLOWER adoption if		
	2.4 Ease of Use =YES			2.6 Salience/Visibility =YES			4.3 Deviation from Norm =YES		
	-> no evidence (t-test, slope_log)			*-> no evidence (t-test, slope_log)*			*-> no evidence (t-test, slope_log)*		
	-> consistent (medians, slope_log)			*-> not consistent (medians, slope_log)*			*-> not consistent (medians, slope_log)*		
TESTS USING LINEAR FUNCTION SLOPES		2.4=YES	2.4=NO		2.6=YES	2.6=NO		4.3=YES	4.3=NO
	count	14	6	count	10	10	count	6	14
	mean	0.009	0.013	mean	0.013	0.008	mean	0.003	0.014
	stdev	0.010	0.011	stdev	0.014	0.006	stdev	0.002	0.014
	median	0.005	0.006	median	0.003	0.007	median	0.002	0.007
	t-test	0.656	ns	t-test	0.517	ns	t-test	0.028	p<.1
	H1: FASTER adoption if			H2: FASTER adoption if			H3: SLOWER adoption if		
	2.4 Ease of Use =YES			2.6 Salience/Visibility =YES			4.3 Deviation from Norm =YES		
	-> no evidence (t-test, slope_lin)			*-> no evidence (t-test, slope_lin)*			*-> supported (t-test, slope_lin)*		
	-> not consistent (medians, slope_lin)			*-> not consistent (medians, slope_lin)*			*-> consistent (medians, slope_lin)*		
	3.4 Protected Niche			3.5 Enabling Policy			3.1 Adopter Type		
TESTS USING LOGISTIC FUNCTION SLOPES		3.4=YES	3.4=NO		3.5=YES	3.5=NO		3.1=INDIV	3.1=xINDIV
	count	5	14	count	3	16	count	11	8
	mean	0.151	0.454	mean	0.118	0.423	mean	0.211	0.600
	stdev	0.080	0.758	stdev	0.062	0.753	stdev	0.190	0.754
	median	0.155	0.161	median	0.046	0.169	median	0.132	0.183
	t-test	0.257	ns	t-test	0.216	ns	t-test	0.406	ns
	H: FASTER adoption if			H: FASTER adoption if			H: FASTER adoption if		
	3.4 Protected Niche =YES			3.5 Market Formation through Policy =YES			3.1 Adopter Type =INDIVIDUAL		
	-> no evidence (t-test, slope_log)			*-> no evidence (t-test, slope_log)*			*-> no evidence (t-test, slope_log)*		
	-> not consistent (medians, slope_log)			*-> not consistent (medians, slope_log)*			*-> not consistent (medians, slope_log)*		
TESTS USING LINEAR FUNCTION SLOPES		3.4=YES	3.4=NO		3.5=YES	3.5=NO		3.1=INDIV	3.1=xINDIV
	count	5	15	count	3	17	count	13	7
	mean	0.003	0.013	mean	0.009	0.011	mean	0.011	0.010
	stdev	0.002	0.014	stdev	0.004	0.014	stdev	0.011	0.011
	median	0.002	0.006	median	0.011	0.004	median	0.006	0.003
	t-test	0.037	p<.1	t-test	0.831	ns	t-test	0.915	ns
	H: FASTER adoption if			H: FASTER adoption if			H: FASTER adoption if		
	3.4 Protected Niche =YES			3.5 Market Formation through Policy =YES			3.1 Adopter Type =INDIVIDUAL		
	-> rejected (t-test, slope_lin)			*-> no evidence (t-test, slope_lin)*			*-> no evidence (t-test, slope_lin)*		
	-> not consistent (medians, slope_lin)			*-> consistent (medians)*			*-> consistent (medians, slope_lin)*		

4.4. Knowledge spillovers

If later adopting regions for an innovation can access and absorb knowledge spillovers from early adopting regions, diffusion speeds may be faster.

H8: Social innovations diffuse faster in later adopting regions.

To test H8, we compared diffusion speeds between early and later adopting regions for a subset of innovations for which we had useable slope parameters from fitted logistic growth or linear functions (or both) for >1 region.

Table 8 and Table 9 summarize the results. Using logistic growth function slopes, only 3 of 12 innovations had faster average diffusion speeds across all later adopting regions compared to the early adopting region. For some innovations, a subset of all later adopter regions had faster diffusion than the early adopting region (column = n_nonEA>EA). But for other innovations, the early adopting region had the fastest diffusion speed. Overall, this is very weak and inconsistent evidence for H8.

Using linear function slopes, 7 of 12 innovations were consistent with H8: a slightly clearer picture. For some innovations, however, the early adopting region had the fastest diffusion speed

Table 8. Comparison of diffusion speeds between early adopting (EA) regions and later adopting (nonEA) regions using slope parameters from logistic growth functions.

		LOGISTIC GROWTH FUNCTION SLOPE PARAMETERS				
SI	**EA region**	**EA**	**mean_nonEA**	**mean_nonEA > EA**	**n_nonEA**	**n_nonEA > EA**
cro	Heidelberg	0.006	-0.223		2	1/2 nonEA faster
eat	Germany	0.011	0.030	mean nonEA faster	4	4/4 nonEA faster
dig	Norway	0.030	0.076	mean nonEA faster	5	4/5 nonEA faster
qui	UK	0.046	0.030		4	0/4 nonEA faster
act	The Netherlands	0.070	-0.021		6	0/6 nonEA faster
eco	US	0.132	0.178	mean nonEA faster	4	3/4 nonEA faster
org	Denmark	0.138	0.087		5	1/5 nonEA faster
ebi	The Netherlands	0.184	0.115		2	1/2 nonEA faster
non	Sweden	0.247	0.118		2	0/2 nonEA faster
coh	Denmark	0.260	0.145		2	0/2 nonEA faster
tel	US	0.291	0.089		6	0/6 nonEA faster
ego	Sweden	0.296	0.164		5	1/5 nonEA faster
mic	India	0.852	-0.069		2	0/2 nonEA faster
sol	New Jersey	3.635	1.448		4	0/4 nonEA faster
dri	Sweden	0.142	0.076		1	0/1 nonEA faster

Table 9. Comparison of diffusion speeds between early adopting (EA) regions and later adopting (nonEA) regions using slope parameters from linear functions.

		LINEAR FUNCTION SLOPE PARAMETERS				
SI		**EA**	**mean_nonEA**	**mean_nonEA > EA**	**n_nonEA**	**n_nonEA > EA**
cro	Heidelberg					
eat	Germany	0.002	0.005	mean nonEA faster	4	3/4 nonEA faster
dig	Norway	0.018	0.019	mean nonEA faster	6	4/6 nonEA faster
qui	UK	0.011	0.006		4	1/4 nonEA faster
act	The Netherlands	0.004	0.000		6	4/6 nonEA faster
eco	US	0.006	0.006		4	3/4 nonEA faster
org	Denmark	0.006	0.002		5	0/5 nonEA faster
ebi	The Netherlands	0.045	0.007		2	0/2 nonEA faster
non	Sweden	0.023	0.030	mean nonEA faster	2	2/2 nonEA faster
coh	Denmark	0.000	0.000		2	0/2 nonEA faster
tel	US	0.001	0.002	mean nonEA faster	6	4/6 nonEA faster
ego	Sweden	0.015	0.026	mean nonEA faster	5	5/5 nonEA faster
mic	India	0.002	0.002	mean nonEA faster	2	1/2 nonEA faster
sol	New Jersey	0.007	0.024	mean nonEA faster	4	2/4 nonEA faster
dri	Sweden	0.012	0.004		3	0/3 nonEA faster

5. Case studies of SI development

We include case studies to go beyond the quantitative indicators and illustrate two important themes: attitudinal precursors and early adoption among a youth cohort.

5.1. Case 1: Attitudinal precursors to eating less meat

Psychological changes, for example in people's attitudes, willingness to change, and intentions are important precursors of behavior change. To characterize the diffusion of social innovations, understanding these psychological changes is imperative. Especially when prevailing norms are challenged, people's views on those behavior may shift. Such shifts in attitudes and intentions often precede changes in behavior (Randall and Wolff, 1994), and can thus be indicative of behavioral trends.

To examine how psychological changes relate to observed behavior, we present a case study on meat consumption. In many countries eating meat is considered normal, tasty, and masculine (Stoll-Kleemann and Schmidt, 2017). Yet, meat consumption is increasingly presented in media as unhealthy and unsustainable, and both vegetarian and vegan food choices are increasingly available in supermarkets and restaurants (Mroz and Painter, 2023; Sievert et al., 2022), challenging the prevailing norm.

We examine 5 countries that have different meat consumption trajectories and compare those to data collected by Ipsos on people's intentions to eat less meat in the period 2014-2022[1] (Figure 9). Intentions refer to people's personal plan to engage in a course of action. People form intentions when they have a positive attitude towards the target behaviour, and are thus also indicative of whether people perceive the behaviour in question positively or negatively (Fishbein and Ajzen, 1977).

Intentions to eat less meat are strongest in India (2014: 50%, 2022: 55%) and Germany (2014: 43%, 2022: 45%). In India, meat consumption is already at a low level (around 6kg/capita). Meat consumption in Germany is much higher (around 85 kg/capita) but shows a decrease over time of around 10 kg/capita. In the United Kingdom, intentions to reduce meat consumption were lower compared to India and Germany (2014: 27%), but increased over time to 36% in 2022, while actual meat consumption mostly remained stable. In the United States (2014: 29%, 2022: 33%) and Japan (2014: 27%, 2022: 29%) those who intend to reduce their meat consumption remains a stable minority. Meat consumption has increased in both of these countries by approximately 10 kg/capita.

We draw three conclusions from this case study. First, the percentage of people who intend to reduce their meat consumption differs significantly per country, indicating that change towards meat-free diets does not happen at the same pace everywhere. Interestingly, intentions to reduce meat consumption in the population also do not seem related to whether meat consumption is relatively high or low compared to other countries. While meat consumption was highest in Germany and the US in 2014, intentions to reduce meat consumption were consistently higher in Germany than the US. Vice versa, while meat consumption was relatively low in Japan, their intentions to reduce were the lowest among the five countries.

Second, changes in intentions and actual meat consumption over time are subtle, with relatively modest increases or decreases observed in the 8 year period under consideration. A significant increase in intentions over time was only observed in the United Kingdom (increasing from 27% to 36%). At the same time, meat consumption has stayed practically stable in the UK. This suggests that changes in intentions may not (immediately) result in changes in behavior and prompts important research questions about when and why intention-behavior gaps occur at a collective level. In the supplemental material, we explore these questions and provide a more in-depth analysis for each country using additional national survey data and contextual information

[1] Measured by IPSOS in 2014, 2020, 2021, and 2022 using the following item: 'Thinking about things you might do in order to limit your own contribution to climate change, how likely or unlikely would you be to make the following changes within the next year? Eating less meat, or replacing the meat in some meals with alternatives such as beans'. The percentage in the text refer to the number of respondents that stated they were 'certain to' reduce their meat consumption, or who found it 'very likely' or 'fairly likely' they would do so.

Third, whether meat consumption in a country is reducing or increasing seems to depend on the percentage of people reporting intentions to reduce. Specifically, in the countries where one-third or fewer of respondents have an intention to reduce their meat consumption, actual meat consumption increased. In countries where intentions to reduce meat consumption exceeded 40%, meat consumption decreased (Germany) or stayed low (India) This tentatively suggests that a critical mass of people endorsing favorable intentions may be required before changes in meat consumption can be observed at the per capita level[2].

Figure 9. Intentions to reduce meat consumption (% of respondents who agree) and actual per capita meat consumption (kg/year) in 5 different countries.

5.2. Case 2: Falling drivers' licenses rates among a subgroup

We assess this case to study the role of early adopter subgroups within a population. There is some evidence that the percentage of young people holding a driver's license has been declining

[2] Notably, this also depends on the context of the specific country. An extended analysis is provided in the Supplemental Material which demonstrates additional examples including China and Brazil, where meat consumption is still increasing despite high intentions to reduce.

across several developed countries (Sivak and Schoettle, 2012). This could be a temporary decline or part of a broader societal shift toward reduced car dependency. We examine two cities (Washington DC, Stockholm) in two countries (US, Sweden) to explore this further.

5.2.1. Stockholm and Sweden

Sweden has experienced a long-term decline in driver's license rates among young individuals. Although national licensure rates remained high until 2008 (around 80%), the percentage of 18-19 year olds with licenses has declined since the early 1980s, stabilizing around 40% after the 2000s (Figure 10). Tracking age cohorts over time helps differentiate between those who forgo obtaining a license entirely (the *cohort effect* in demographics) and those who delay obtaining one (the *period effect* in demographics). Cohort effects reduce overall numbers of licenses, period effects do not. For Sweden, Kågeson (2014) found the period effect dominated the cohort effect among 18-19 year olds over three decades from 1983 to 2012 (Kågeson, 2014).

In Stockholm, rates are significantly lower than the national average, but among 18-19 year olds has been increasing to 33% by 2023. Changes in driver's licenses have not affected car ownership rates in Stockholm which have remained stable (at a low) rate of some 360 vehicles per 1000 inhabitants between 2003 and 2023.since 2018. In Stockholm, the period effect is overwhelmed by the effects of migration that significantly increase the size of the young cohort. As driver's license rates in the 18-19 year old age group have been increasing against a stable background rate for the population as a whole (Figure 10), the cohort effect is likely to be comparatively smaller than the period effect.

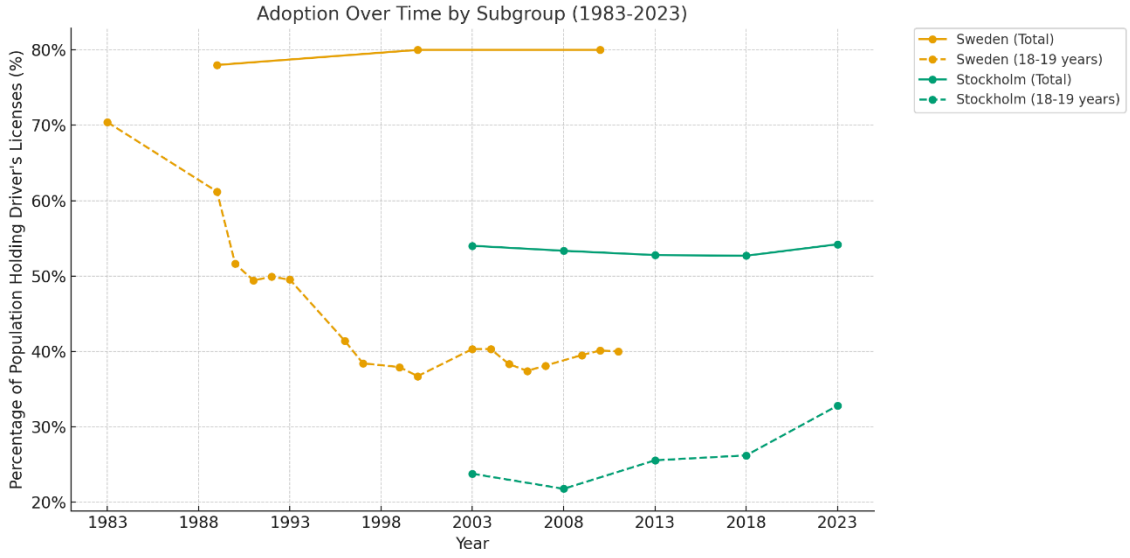


Figure 10. Adoption of driver's licenses by subgroup and by broader population in Stockholm and Sweden.

Source: 2003-2023: Transport Analysis Sweden (driver's licenses, unpublished); Statistics Sweden (population);1983:2003: Kågeson 2014, Sivak & Schoettle 2011.

Multiple factors contribute to the decline in driver's licenses in Sweden (Kågeson, 2014):

- *Urban migration & urbanization*: Availability of good public transport services in cities. International migrants also less likely to obtain driver's license.
- *Social change*: Weakening of driver's licenses as a social marker of adulthood, particularly in rural areas (Forward et al., 2010).
- *Economics*: Youth unemployment, rising costs of car ownership, and transaction costs of obtaining a driver's license (regulatory barriers, stricter tests) (Kökort, 2025).
- (*Demographics*: The gender gap closing is a countervailing trend pushing up driver's licenses up as more women seek access to driving particularly among younger age groups).

5.2.2. United States

In the U.S., driver's license holding rates among 16- and 18-year-olds have significantly declined. Figure 11 shows that the percentage of licensed 16-year-olds fell from 46% in 1983 to 25% in 2020, while for 18-year-olds, it dropped from 80% to 58%. This trend was identified as early as 2010, noticing a peak in the rates of driver's license holders in the age group 40 to 44 years of age (Sivak and Schoettle, 2012).

A comparison of age cohorts shows that rates among 18- and 19-year-olds have dropped, though the gap narrows in the 30–40-year age range. Similarly to Sweden, there is no clear indication of a "Peak Car" phenomenon in the U.S., though a decline in license holding rates among individuals under 44 has been reported (Sivak and Schoettle, 2016). Economic constraints, such as increasing vehicle costs and the diminishing advantages of private cars over public transport, may explain this trend.

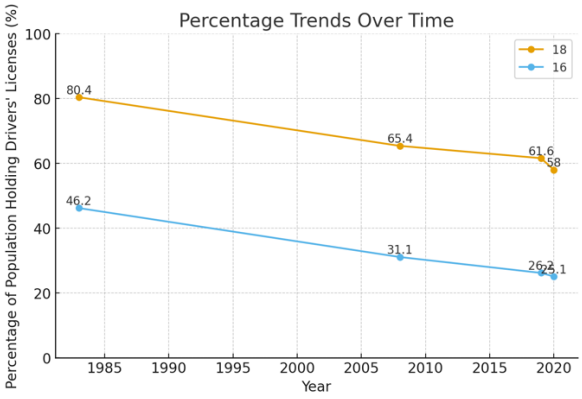


Figure 11. Percentage of U.S. licensed drivers with 16 and 18 years old over time (1983-2020). Source: US Federal Highway Administration.

5.2.3. Comparing Sweden and the US

The observed decline in driver's license rates among younger generations is a persistent trend in both Sweden and the United States. This shift is largely influenced by economic factors and changing attitudes toward car ownership, further amplified by urbanization and digitalization.

Although both Sweden and the U.S. show declining rates among young people, the patterns and underlying causes vary. In Sweden, rates have been declining in large cities like Stockholm since the economic crisis of the 1990s and have since stabilized. A recent increase in rates, particularly among women, suggests that social factors may also be contributing to these observed changes. Conversely, in the U.S., the decline in young people obtaining driver's licenses is a more recent trend. Economic factors, such as rising vehicle costs and increased digital connectivity, appear to play a significant role in this shift.

The dynamic trends of the decline in the percentage of young people holding driver's licenses conforms to classical diffusion patterns, albeit with some exceptions. The speed of diffusion (Δt) is with 17 years fast, reflecting the twin effects of declining relative advantage (benefits of driving a car vs. public transport especially in cities), increasing adoption effort (direct economic and transaction costs of obtaining a driver's license) as well as social network (peer) effects that propagate a new "young urbanite" car-free lifestyle.

6. Conclusions

Our analysis shows that it is both possible and insightful to quantify the diffusion dynamics of social innovations and so emphasize their importance alongside low-carbon technological innovations (like solar PV, electric vehicles, energy efficient goods) for which both data and theory are more readily available.

6.1. Dataset and descriptive statistics

In constructing the Diffusion of Social Innovations dataset, we synthesized time series data characterizing the diffusion of 27 social innovations relevant to HwL futures. Time series length averaged 27.4 years (range of 4-163), with an average of 3.3 spatial scales per innovation (range 1-8) including an early adopting city or country.

- We cleaned, transformed where necessary, and harmonized data to ensure comparability across innovations, time periods, and adoption contexts. In particular we fitted logistic growth and linear functions to time series subject to goodness of fit criteria so we could use slope parameters as comparable measure of diffusion speed over the innovation lifecycle captured in the data.
- Our final dataset for analysis comprised 383 time series of which 117 described early adopting regions (across our full sample of 27 social innovations). From these, a subset of 313 time series could be adequately described by logistic growth models of which 101 described early adopting regions (for a reduced sample of 24 social innovations).

We took an initial look at the data by calculating descriptive statistics and found the following:

- Reasonable fits of market share data in early adopting region to logistic curves for all 23 SIs. 3 cases in which data reviewers disagreed.

- Median logistic growth for preferred adoption metric among early adopters across 23 social innovations is 0.14. with larger dispersion.
- Goodness of fit is uncorrelated with growth rate, but range of data covered (relative to asymptote) is positively correlated with growth.
- Growth parameters for logistic fits are poorly correlated with calculations of linear growth rates, among early adopters across 22 social innovations.
- Among the three categories of SIs, business model innovations have the highest median growth rate. This is true for both early adopter regions and all regions.

6.2. Comparisons and hypothesis testing

We compared growth rates among early adopter regions for social innovations (DOSI data) to those for technological innovations (HATCH) and found:

- Distribution of logistic growth rates for early adopter SIs is similar to that for technological innovations. Shape of distribution is similar and medians are similar.
- Comparing growth in EA SI categories to technological categories shows that the three SI categories span the distribution of pooled SI and TIs: business model is at the 82nd percentile, institutional is at the 68th, and behavioral is at the 25th.

Focusing on the formative phase for social innovations, we tested if formative phase duration was associated with faster diffusion.

- Using a subsample of 8 innovations, we found this was the case when using logistic growth function slope parameters as a measure of diffusion speed. However, this association dropped away when using linear function slopes.
- We found suggestive evidence of a relationship between formative phases and diffusion speeds as would be expecting, but needs further testing on a larger innovation sample.

To understand the determinants of diffusion speed, we tested if certain innovation characteristics were associated with faster diffusion. Our hypothesis testing on determinants of diffusion speeds so far has had disappointing results. However, we recognize that to detect significant bivariate relationships in a small but highly diverse sample of innovations with strong outliers requires a very strong signal. So far we have only tried to detect this signal in early adopting regions.

- We found no evidence supporting our hypotheses that higher ease of use (accessibility) or higher social visibility help explain faster diffusion speeds.
- We tested if certain adoption contexts were associated with faster diffusion.
- We found no evidence supporting our hypotheses that policy dependence or protected niches help explain faster diffusion speeds.
- We found weak evidence (based on linear function slopes) supporting our hypothesis that lower deviation from social norms helps explain faster diffusion speeds.

We also looked for evidence of international *knowledge spillovers by testing* if diffusion accelerated as innovations diffused out of early adopting regions into later adopter regions that could potentially benefit from knowledge spillovers. We found only weak and inconsistent evidence supporting this spatial diffusion hypothesis.

6.3. Case studies on attitudes and subgroup cohorts

The first case study looked at 5 countries to assess the role that attitudinal changes had in evidence of change in quantity of meat eating. Attitudes show changes in intentions and actual meat consumption over time are subtle, with relatively modest increases or decreases observed in the 8 year period under consideration.

- We see large variation in attitudes across countries.
- There is some evidence that higher intentions to eat less meat lead to declines in meat, whereas countries with lower intentions to change do not decline.

The second case study looked at driver's license adoption among teenagers. The observed decline in driver's license rates among younger generations is a persistent trend in both Sweden and the United States.

- This shift is largely influenced by economic factors and changing attitudes toward car ownership, further amplified by urbanization and digitalization.
- The speed of diffusion (Δt=17 years) is fast, reflecting the twin effects of declining relative advantage (benefits of driving a car vs. public transport especially in cities), increasing adoption effort (direct economic and transaction costs of obtaining a driver's license) as well as social network (peer) effects that propagate a new "young urbanite" car-free lifestyle.

6.4. Further research

The results of this work provide some appreciation of the wide dispersion in innovation dynamics across the 27 SIs we assess in this study. They also point to areas of further work, many of which we plan to address in the next iteration of this study:

- Extend hypotheses to cover all indicators.
- Report full selection criteria for curve fitting.
- Add tables of extracted parameters: measures and comparisons of adoption speed.
- Add description of how outliers are handled because they seem to have an important effect on the results.
- Update comparisons to TIs using HATCH 2.0 and choose early adopter country for each technology.

- Reconcile mismatch between spatial scales used for formative phase duration and spatial scales in the EA time series. Add data from literature for formative phase duration for other innovations.
- Additional H testing on non1.1 time series e.g. (1) bivariate relationships = similar form to diffusion, sequencing, and rates of change? (2) groupwise comparisons (innovations with / without x) on diffusion characteristics.
- Add non-parametric difference tests (Mann-Whitney U)

In the longer term the expansion of the data set to a larger set of SIs would increase reliability of results. Our purpose with this paper is to generate a proof concept to help guide and motivate the effort to a larger data collection and analysis project.

7. Acknowledgements

Authors gratefully acknowledge the funding from the Energy Demand changes Induced by Technological and Social innovations (EDITS) project, coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and the International Institute for Applied Systems Analysis (IIASA) and funded by the Ministry of Economy, Trade, and Industry (METI), Japan. Furthermore, authors appreciate the constructive feedback received from participants at the EDITS Annual and Quarterly Meetings.

8. References

Allcott, H., Rogers, T., 2014. The Short-Run and Long-Run Effects of Behavioral Interventions: Experimental Evidence from Energy Conservation. American Economic Review 104, 3003–3037. https://doi.org/10.1257/aer.104.10.3003

Avelino, F., Wittmayer, J.M., Pel, B., Weaver, P., Dumitru, A., Haxeltine, A., Kemp, R., Jørgensen, M.S., Bauler, T., Ruijsink, S., O'Riordan, T., 2019. Transformative social innovation and (dis)empowerment. Technological Forecasting and Social Change 145, 195–206. https://doi.org/10.1016/j.techfore.2017.05.002

Bento, N., Wilson, C., 2016. Measuring the duration of formative phases for energy technologies. Environmental Innovation and Societal Transitions 21, 95–112. https://doi.org/10.1016/j.eist.2016.04.004

Bento, N., Wilson, C., Anadon, L.D., 2018. Time to get ready: Conceptualizing the temporal and spatial dynamics of formative phases for energy technologies. Energy Policy 119, 282–293. https://doi.org/10.1016/j.enpol.2018.04.015

Bouchard, M.J., 2013. Innovation and the Social Economy: The Quebec Experience. University of Toronto Press. https://doi.org/10.3138/9781442695092

Burke, M.K., Pugh, R., Soetanto, D., Owusu-Kwarteng, A., Jack, S.L., 2024. The engaged university delivering social innovation. J Technol Transf 49, 2056–2079. https://doi.org/10.1007/s10961-024-10091-9

Dall-Orsoletta, A., Cunha, J., Araújo, M., Ferreira, P., 2022. A systematic review of social innovation and community energy transitions. Energy Research & Social Science 88, 102625. https://doi.org/10.1016/j.erss.2022.102625

Dietz, T., Gardner, G.T., Gilligan, J., Stern, P.C., Vandenbergh, M.P., 2009. Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. Proceedings of the National Academy of Sciences 106, 18452–18456. https://doi.org/10.1073/pnas.0908738106

EC, Therace, A., Hubert, A., Dro, I., 2011. Empowering people, driving change : social innovation in the European Union. Publications Office of the European Union.

Fishbein, M., Ajzen, I., 1977. Belief, Attitude, Intention, and Behavior: An Introduction to Theory and Research. Philosophy and Rhetoric 10, 130–132.

Geels, F.W., 2024. Advanced Introduction to Sustainability Transitions. Edward Elgar Publishing.

Grimm, R., Fox, C., Baines, S., Albertson, K., 2013. Social innovation, an answer to contemporary societal challenges? Locating the concept in theory and practice. Innovation: The European Journal of Social Science Research 26, 436–455. https://doi.org/10.1080/13511610.2013.848163

Grubler, A., 1990. The rise and fall of infrastructures. Physica-Verlag, Heidelberg.

Grubler, A., Nakicenovic, N., Victor, D.G., 1999. Dynamics of energy technologies and global change. Energy Policy 27, 247–280.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., De Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., Valin, H., 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat Energy 3, 515–527. https://doi.org/10.1038/s41560-018-0172-6

Kågeson, P., 2014. The causes and effects of declining driver license holdings in Sweden. Working papers in Transport Economics, Working papers in Transport Economics.

Khanna, N.Z., Zhang, J., Lu, H., Feng, W., Johnson-Wang, M., Zhou, N., 2023. Conceptualizing demand-side technological and social innovations in modeling pathways to carbon neutrality. Energy Research & Social Science 100, 103115. https://doi.org/10.1016/j.erss.2023.103115

Koukoufikis, G., 2021. Social Innovation and the Energy Transition-towards a Working Definition. European Commission.

Mikkonen, I., Gynther, L., Matschoss, K., Koukoufikis, G., Murauskaite, I., Uihlein, A., 2020. Social innovations for the energy transition [WWW Document]. JRC Publications Repository. https://doi.org/10.2760/555111

Mroz, G., Painter, J., 2023. What do Consumers Read About Meat? An Analysis of Media Representations of the Meat-environment Relationship Found in Popular Online News Sites

in the UK. Environmental Communication 17, 947–964. https://doi.org/10.1080/17524032.2022.2072929

Nemet, G., Greene, J., 2022. Innovation in low-energy demand and its implications for policy. Oxford Open Energy. https://doi.org/10.1093/OOENERGY/OIAC003

Nemet, G., Greene, J., Müller-Hansen, F., Minx, J.C., 2023a. 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

Nemet, G., Greene, J., Zaiser, A., Hammersmith, A., 2023b. Historical Adoption of Technologies (HATCH) Dataset. https://doi.org/10.5281/zenodo.10035735

Nesta, L., Vona, F., Nicolli, F., 2014. Environmental policies, competition and innovation in renewable energy. Journal of Environmental Economics and Management 67, 396–411. https://doi.org/10.1016/j.jeem.2014.01.001

Niamir, L., Verdolini, E., Nemet, G.F., 2024. Social innovation enablers to unlock a low energy demand future. Environ. Res. Lett. 19, 024033. https://doi.org/10.1088/1748-9326/ad2021

Randall, D.M., Wolff, J.A., 1994. The time interval in the intention-behaviour relationship: Meta-analysis. British Journal of Social Psychology 33, 405–418. https://doi.org/10.1111/j.2044-8309.1994.tb01037.x

Rayner, S., Malone, E.L., 1997. Human choice and climate change. Volume 1: The societal framework (No. BATT-0090/XAB). Battelle Memorial Inst., Columbus, OH (United States).

Rogers, E.M., 2003. Diffusion of innovations, 5th ed. Free Press, New York.

Sievert, K., Lawrence, M., Parker, C., Russell, C.A., Baker, P., 2022. Who has a beef with reducing red and processed meat consumption? A media framing analysis. Public Health Nutrition 25, 578–590. https://doi.org/10.1017/S1368980021004092

Sivak, M., Schoettle, B., 2016. Recent Decreases in the Proportion of Persons with a Driver's License across All Age Groups.

Sivak, M., Schoettle, B., 2012. Eco-driving: Strategic, tactical, and operational decisions of the driver that influence vehicle fuel economy. Transport Policy 22, 96–99. https://doi.org/10.1016/j.tranpol.2012.05.010

Sovacool, B.K., Brugger, H., Brunzema, I., Dańkowska, A., Wemyss, D., Vernay, A.-L., Betz, R., Avelino, F., de Geus, T., Dembek, A., 2023a. Social innovation supports inclusive and accelerated energy transitions with appropriate governance. Communications Earth & Environment 4, 289.

Sovacool, B.K., Brugger, H., Brunzema, I., Dańkowska, A., Wemyss, D., Vernay, A.-L., Betz, R., Avelino, F., de Geus, T., Dembek, A., Duetschke, E., Hielscher, S., Iskandarova, M., Müller, L., Musiolik, J., Ranville, A., Schleich, J., Stasik, A., Strumińska-Kutra, M., Winzer, C., Wittmayer, J., Rogge, K.S., 2023b. Social innovation supports inclusive and accelerated energy transitions with appropriate governance. Commun Earth Environ 4, 1–11. https://doi.org/10.1038/s43247-023-00952-w

Steg, L., Veldstra, J., de Kleijne, K., Kılkış, Ş., Lucena, A.F.P., Nilsson, L.J., Sugiyama, M., Smith, P., Tavoni, M., de Coninck, H., van Diemen, R., Renforth, P., Mirasgedis, S., Nemet, G., Görsch, R., Muri, H., Bertoldi, P., Cabeza, L.F., Mata, É., Novikova, A., Caldas, L.R., Chàfer, M., Khosla, R., Vérez, D., 2022. A method to identify barriers to and enablers of implementing climate change mitigation options. One Earth 5, 1216–1227. https://doi.org/10.1016/j.oneear.2022.10.007

Stoll-Kleemann, S., Schmidt, U.J., 2017. Reducing meat consumption in developed and transition countries to counter climate change and biodiversity loss: a review of influence factors. Reg Environ Change 17, 1261–1277. https://doi.org/10.1007/s10113-016-1057-5

Verain, M.C.D., Reinders, M.J., Bouwman, E.P., Dagevos, H., 2024. Gradual behaviour change towards meat reduction revisited: Applying the decisional balance scale in a Dutch study. Appetite 203, 107712. https://doi.org/10.1016/j.appet.2024.107712

Wiedenhofer, D., Streeck, J., Wiese, F., Verdolini, E., Mastrucci, A., Ju, Y., Boza-Kiss, B., Min, J., Norman, J., Wieland, H., Bento, N., León, M.F.G., Magalar, L., Mayer, A., Gingrich, S., Hayashi, A., Jupesta, J., Ünlü, G., Niamir, L., Cao, T., Zanon-Zotin, M., Plank, B., Vélez-Henao, J., Masanet, E., Krey, V., Akimoto, K., Grubler, A., Ruijven, B. van, Pauliuk, S., 2024. Industry Transformations for High Service Provisioning with Lower Energy and Material Demand: A Review of Models and Scenarios. Annual Review of Environment and Resources 49, 249–279. https://doi.org/10.1146/annurev-environ-110822-044428

Wilson, C., Grubler, A., Gallagher, K.S., Nemet, G.F., 2012. Marginalization of end-use technologies in energy innovation for climate protection. Nature Climate Change 2. https://doi.org/10.1038/nclimate1576

Wilson, C., Grubler, A., Nemet, G., Pachauri, S., Pauliuk, S., Wiedenhofer, D., 2023. The'high-with-low'scenario narrative: Key themes, cross-cutting linkages, and implications for modelling.

Ziervogel, G., Hamann, R., 2024. The potential of social innovation to shift the limits to climate adaptation. Current Opinion in Environmental Sustainability 71, 101491. https://doi.org/10.1016/j.cosust.2024.101491

Appendix

This appendix provides further detail supporting information for the analysis discussed in the main text.

A1. List of social innovations

DATA COLLECTED			
	Behavioral	**Business model**	**Institutional**
	car ownership	sustainable fashion	smoking less
	co-housing	fashion, textile recycling	climate activism
	driving licences	firm ESG reporting	postage stamps
	teleworking	passive buildings, retrofits	energy communities
	living space	e-commerce	
	organic food	food waste reduction	
	car size	microfinance in G.South	
	eating less meat		
	active travel		
	low-carbon travel		
DATA COMING?			
	e-bikes	1-stop shops (bldg retrofits)	digital skills
	smartphone use	energy service companies	e-government
	climate perceptions	ride hailing platforms	digital payments
	post-materialist values	shared pooled mobility	climate literacy
	climate policy support	solar roof leasing	
		solar balconies	

A2. Original taxonomy of social innovations

Adoption Unit	Category	Definition
society	social	norms, social organizations, collective patterns of behavior
society	institutional	rules, types of organization, practices, policies
individual	behavioural	individual or household level, discrete behaviours
individual	cognitive	individual values, beliefs, perceived norms
individual	lifestyle	identity-related or patterned behavioural or cognitive shifts

individual	consumer preference	technology adoption expenditure or capital investment-related
firm	business model	ways of providing services, firm strategies & operations, value propositions for end-users
firm	finance	ways of financing service provision

A3. Characteristics of innovations and adoption contexts for technological innovations.

Technology characteristics analogous to social innovations.

Variable	Hypothesis	Expected direction	Direction found
First year of commercialization	Later years of first commercialization will be associated with faster growth than earlier.	Positive	Positive
Technological Lifetime	Shorter technological lifetimes will be associated with faster growth than longer lifetimes.	Negative	Negative
Material Use ($/kg)	Low material use will be associated with faster growth than high material use.	Negative	Positive
Granularity	Higher granularity will be associated with faster growth than lower granularity (in other words, lower price will be associated with faster growth).	Positive	Positive
Complexity	Simple will be associated with faster growth than more complex.	Negative	Negative
Need for Customization	Less need for customization will be associated with faster growth than more.	Negative	Mixed
Type of Adopter	Individuals will adopt more quickly than firms, but technologies available to both firms and individuals will benefit from multiple markets.	Positive	Negative/Mixed
Requires Feedstock	No feedstock requirement will allow for faster growth.	Negative	
Replacement	Replacing an existing technology will allow for faster growth.	Positive	Negative
Category	--	--	--

Adoption environment characteristics

Variable	Hypothesis	Expected direction	Direction found
Country income level	Rate of adoption in early stages of technology growth is influenced by the level of economic development in a country. Higher levels of wealth allow for faster technology adoption.	Positive	
Spending on tech development	More spending on technological R&D associated with faster technology adoption.	Positive	
Type of government	Democracies allow for faster growth of technologies, whereas dictatorships slow technology adoption.	--	
Institutional capacity to pass, support, coordinate policies	For large, non-industrial technologies, higher state capacity is associated with faster growth.	Positive	
Membership in international trade organizations	Membership in trade organization allows for higher trade, therefore faster technology adoption.	Positive	
Public acceptance of technology	Higher public acceptance for science and technologies allows for faster technology adoption.	Positive	

A4. Definitions of social innovations.

We have found a wide array of definitions of SI in the literature. Most of them do not correspond well to our thinking, which is focused on 1) distinguishing innovations that are mainly social, albeit with a hardware component and 2) those which are primarily hardware but with a social component. Many definitions consider social innovations those that provide benefits for society. We find this definition too broad and not suited to our purpose. We thus need to redefine and distinguish our use of "social innovation" from much of the literature or perhaps adopt a different term.

Some definitions from the literature include:

"normative desire for deeper sustainability-oriented changes in lifestyles and social practices" (Geels, 2024)

Although in this def we see the same dismissive consideration of the tech vs nontech distinction, which to use is central

An important definition is from the European Commission (EC et al., 2011):

Social innovation has been applied to climate adaptation (Ziervogel and Hamann, 2024).

Another definition the social replies to the process of innovation (Burke et al., 2024): "social innovation involves bringing individuals, organisations and communities together through supporting entrepreneurship, collaboration and mutual learning capacities both within and beyond the university setting."

Also (Sovacool et al., 2023b)

"Social innovation in energy (SIE) encompasses changes across elements as varied as new patterns of energy storage, the coordination of energy efficiency efforts, citizen assemblies to reduce greenhouse gas emissions or shared forms of finance and ownership such as crowdsourcing or cooperatives[12,13,14]. In our current times of multiple, interrelated, and existential system failures, social innovation can mobilize creativity and entrepreneurship to overcome these, thereby contributing to transforming our systems of production and consumption[15,16,17]. For example, Ravazzoli and colleagues explored the potential of social innovation across rural areas in Europe and found that it produced strong positive "cross-sectoral (societal, economic, environmental, and governmental) and multi-level impacts (on individuals, community, and society)" that have significantly "improved the societal well-being, and contributed to the reduction of certain forms of marginality"[18]. Lupi et al.[19] write that social innovation in the form of collective action initiatives has served to raise environmental awareness, promoted the mobilization of citizens, and fostered social inclusion. Similarly, the Joint Research Centre of the European Commission writes that social innovation in the energy sector could satisfy human and societal needs while in parallel empowering vulnerable social groups alongside

“cultivating civic traditions of trust, equity, and solidarity within and beyond the spatial context on which they occur”[20,21].

ERC report on Social Innovations for the energy transition (Mikkonen et al., 2020):

“Social innovation comes in place to offer tools to support the transformation of existing structures towards a low-carbon society. Social innovation contributes to new social practices, institutions and systems, and its ultimate goal is social change, while actions often take place decentralised at the level of collectives or groups. Therefore, the impacts of social innovations can be diffused more easily on individual and community levels promoting sustainable behaviour and lifestyle changes.”

The successful social innovations appear to have some features in common. They have a clear vision and organizational capabilities as project plans or business plans are often prepared in advance. At the same time, there has been agility to adjust to changing circumstances or to seize opportunities and indicate tolerance for delays on the advancement of the project. Co-operation with local policy-makers and municipalities as well as other partners has been very important. In addition, it was observed that they put a strong focus on soft skills like communication and marketing abilities, and the capacity to cooperate and work together. Technical, economic, and juridical skills have been in high demand as well and often provided by volunteers if the affected communities lacked the competence.

Indeed, there is a variety of ways that social innovation has been defined and understood (Angelidou and Psaltoglou, 2017; Ayob et al., 2016; van der Have and Rubalcaba, 2016). Some scholars consider social innovation as a necessary element to complement technological innovation in order to enable a transformation towards more sustainable societies. However, social innovations are more than simply non-technical enhancements to products (Cajaiba-Santana, 2014). Repo and Matschoss (2019) define social innovation as an innovation that addresses social needs or has a social impact and find in their empirical study that social innovations emerge less due to technological or political but rather depend on factors that have a social dimension. Indeed, social networks and social processes create important opportunities for societal development and help make societies more sustainable, cohesive and resilient through inclusive practices, coproduction and grassroots initiatives (Grimm et al., 2013).

Cajaiba-Santana (2014) similarly elaborates that social innovation contributes to new social practices, institutions and systems, and that its ultimate goal is social change, while respective actions often take place at the level of collectives or groups. Manzini (2014, p.57) defines social innovations in the following way: “social innovations are widely understood as new ideas that aim at meeting social goals”. Mulgan (2006, p. 146) defines that “social innovation refers to innovative activities and services that are motivated by the goal of meeting a social need and that are predominantly diffused through organizations whose primary purposes are social”. Angelidou and Psaltoglou (2017, p. 114) characterise the concept in more detail by stating that “social innovations are new solutions (products, services, models, markets, processes etc.) that simultaneously meet a social need (more effectively than existing solutions) and leads to new or improved capabilities

and relationships and better use of assets and resources". They, thus, also resort to the view of emphasising the establishment of new social practices. Howaldt and Hochgerner (2018) highlight that such self-organisation in collectives of groups is an approach attempting to solve market challenges that emerge rather from bottom-up than being a top-down response.

Also (Khanna et al., 2023):

(Dall-Orsoletta et al., 2022):

SI = "innovations that contribute to the low- carbon energy transition, civic empowerment, and social goals through initiatives such as new forms of governance, social configurations, supportive policies and regulations, and new business models."

"SI has an important role in local transitions but limited power to challenge the regime and scale-up."

"community-led actions are in a unique position to access local tacit knowledge, influence individual behavior, and use them to build more sustainable cities."

(Avelino et al., 2019)

"Change in social relations, involving new ways of doing, organising, knowing and framing."

The Bureau of European Policy Advisors (BEPA)defines SI as "innovations that are social both in their ends and in their means"and argues that they provide an effective way to "empower people" and "drive societal change"(BEPA,2010).

A5. Full set of priority indicators for measuring variables associated with social innovation diffusion speed and determinants.

Table. Priority list of indicators to measure diffusion variables.

#	Indicator	Description of Indicator	Question to guide choice of metric	Example metrics [time series unless noted]
1.1	Adoption over time *	adoption or use (diffusion curve) *	What share of potential users is reached each year? What level or amount of usage is there each year?	# adopters, market share (%) (& total market size e.g. # population)
1.2	Formative phase	initial (slow) adoption phase	In what year was the innovation first used?	year of first (sequential) appearance
2.1	Learning	cost and performance attributes	Is the innovation improving in performance characteristics over time?	cost
2.2	Relative advantage	profitability	Is the innovation profitable? Cost-reducing?	cost relative to incumbent
2.3	Relative advantage	co-benefits (non-monetary)	Does the innovation provide non-monetary benefits (e.g., for health, wellbeing, livelihoods)?	e.g., health or wellbeing benefits
2.4	Ease of use	ease of use, accessibilty	Is the innovation easy to use or access? (e.g., doesn't require new skills; opposite of complex)	new skills or training requirements
2.5	Variety	choice availability	Are there alternative varieties or types of the innovation available, offering choice to adopters?	choice options

#	Indicator	Description of Indicator	Question to guide choice of metric	Example metrics [time series unless noted]
2.6	Visibility	social signalling	Can others easily observe the innovation being used? Does use of the innovation link to or communicate social identity or status?	[categorical - e.g., yes/maybe/no]
2.7	Granularity	adopter 'unit size'	How many people are required for a single adoption of this innovation?	minimum # people in 'adoption unit'
2.8	(Perceived) uncertainty & risk	triallability	Can the innovation be tried out before having to commit? Is adoption easily reversible with no/low sunk cost?	[categorical - e.g., yes/maybe/no]
2.9	Inter-dependence (with hardware)	link to physical artefact	Is the innovation inter-dependent with adoption of physical technology or hardware?	[categorical - e.g., yes/maybe/no]
2.10	Inter-dependence (with hardware) - unit size	unit size of linked physical artefact	If the innovation is linked with physical technology, what is the average unit cost of that technology?	$/unit (for typical unit)
3.1	Adopter type	adopter 'unit'	Who/what uses or adopts the innovation (in different market niches)?	[categorical - e.g., individual, firm, collective]
3.2	Adopter characteristics	sociodemographics	What are average or typical sociodemographic characteristics of adopters?	income, age, gender
3.3	(Perceived) uncertainty & risk	knowledge generation	Is social uncertainty addressed by knowledge stocks generated through research, discovery, or experimentation?	scientific publications, patents

#	Indicator	Description of Indicator	Question to guide choice of metric	Example metrics [time series unless noted]
3.4	(Perceived) uncertainty & risk	protected niches	Are there no/low risk or cost-insensitive adoption contexts for this innovation?	[categorical - e.g., yes/maybe/no]
3.5	Market formation	entrepreneurial activity	Is there entrepreneurial activity around this innovation?	start up companies, deals, early-stage VC investments
3.6	Market formation	policy support	Is there supportive policy or enabling legal or regulatory frameworks for this innovation?	[categorical - e.g., yes/maybe/no]
4.1	Knowledge flows	salience	Is information about the innovation communicated socially? Is the innovation salient, discussed, or socially visible?	[categorical / "expert judgement"! - e.g., yes/maybe/no]
4.2	Knowledge flows	mass media	Is information about the innovation communicated through mass media (or if relevant - scientific publications)?	media mentions
4.3	Compatibility	extent of deviation from norm	Does early adoption of this innovation deviate markedly from prevailing social norms?	[categorical - e.g., yes/maybe/no] related to (referent group) identity or mainstream culture
4.4	Provisioning system	(social) infrastructure size	What number of people or actors is the minimum possible for providing the innovation?	min # actors in provisioning system
4.5	Infrastructure dependence	physical infrastructure dependence	Does use of the innovation rely on or integrate into physical infrastructure?	[categorical - e.g., yes/maybe/no]

#	Indicator	Description of Indicator	Question to guide choice of metric	Example metrics [time series unless noted]
4.6	Standardisation	rules, standards, quality assurance	Is the innovation standardised or otherwise quality assured?	presence of standards, rules, labels, or similar

Notes:
for indicators denote type : 1 = diffusion over time and space; 2 = innovation characteristics; 3 = adoption contexts; 4 = innovation characteristics + adoption contexts
* diffusion measured at different spatial scales or 'adoption niches' relevant for the innovation (e.g., early-adopting social group -> city -> country)

A6. Longer case study on eating less meat

Supplementary analysis: how do changes in people's attitudes and intentions towards meat consumption relate to actual levels of meat consumption?

Important precursors for changes in behaviour include people's attitudes (i.e., the extent to which they evaluate a particular behaviour positively or negatively) and people's intentions to change their behaviour (i.e., people's personal commitment to a course of action) (e.g., (Armitage & Christian, 2003). In this case study, we examine how people's attitudes and intentions towards reducing meat consumption are changing over time, how these changes relate to changes in actual meat consumption.

Intentions to reduce meat consumption for the climate across the globe

As part of their Earth Day report series, Ipsos has examined people's attitudes and behaviours related to climate change in 28 countries using surveys of approximately 500-1,000 respondents per country[3] (Ipsos, 2020, 2021, 2022). In 2020, 2021, and 2022, this survey included the following item, which we use as an indicator of people's intentions to reduce their meat consumption:

'Thinking about things you might do in order to limit your own contribution to climate change, how likely or unlikely would you be to make the following changes within the next year? Eating less meat, or replacing the meat in some meals with alternatives such as beans'.

We examine the percentage of respondents that stated they were 'certain to' reduce their meat consumption, or who found it 'very likely' or 'fairly likely' they would do so. Overall, exactly half of the countries (14 out of 28, 50%) report an increasing number of people who indicate that they find it likely or certain that they will reduce their meat consumption (> +3,5% (the error margin estimated by IPSOS) between 2020 and 2022).

[3] A sample size of 1000 participants were sampled in most countries. In the following countries, a sample size of 500 was collected: Argentina, Belgium, Chile, Colombia, Hungary, India, Malaysia, Mexico, the Netherlands, Peru, Poland, Russia, Saudi Arabia, South Africa, South Korea, Sweden, Switzerland and Turkey. Representative data was collected in: Argentina, Australia, Belgium, Canada, France, Germany, Great Britain, Hungary, Italy, Japan, the Netherlands, Norway Poland, South Korea, Spain, Sweden, and United States. Data from: Brazil, Chile, mainland China, Colombia, India, Malaysia, Mexico, Peru, Russia, Saudi Arabia, South Africa and Turkey are not nationally representative, with urban, educated, and affluent respondents being overrepresented.

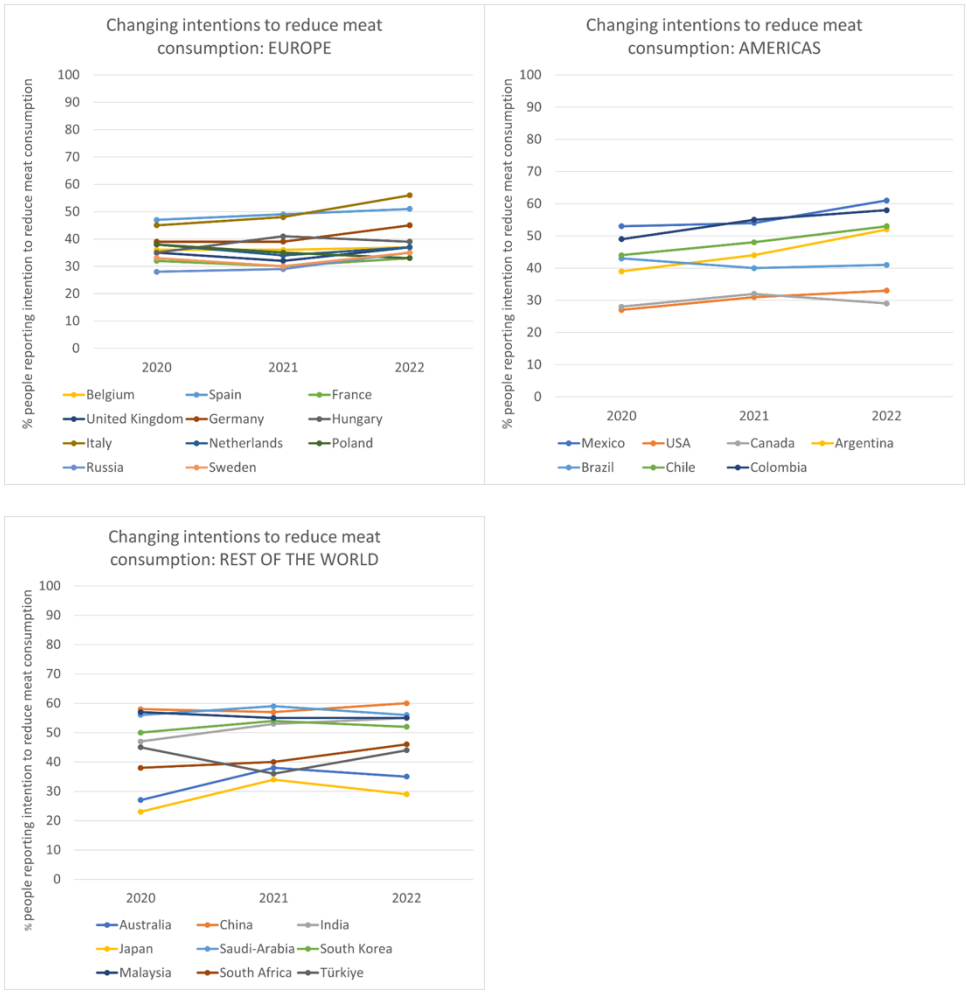


Figure 1. Changing intentions to reduce meat consumption in 28 countries across the globe. Data are retrieved from the Ipsos 2020, 2021, and 2022 Earth Day reports.

This same question about eating less meat was also included in a 2014 survey conducted in 12 countries (Bailey et al., 2014), allowing for a trend analysis across an 8-year time period (2014-2022) for these countries. Looking at the countries for which 2014 data is available, 7 out of 12 report a higher percentage of people (> +3,5%) with the intention to reduce their meat consumption in 2022 compared to 2014, with the strongest increases observed in Italy (44% to 56%), the UK (26% to 37%), and Russia (25% to 35%).

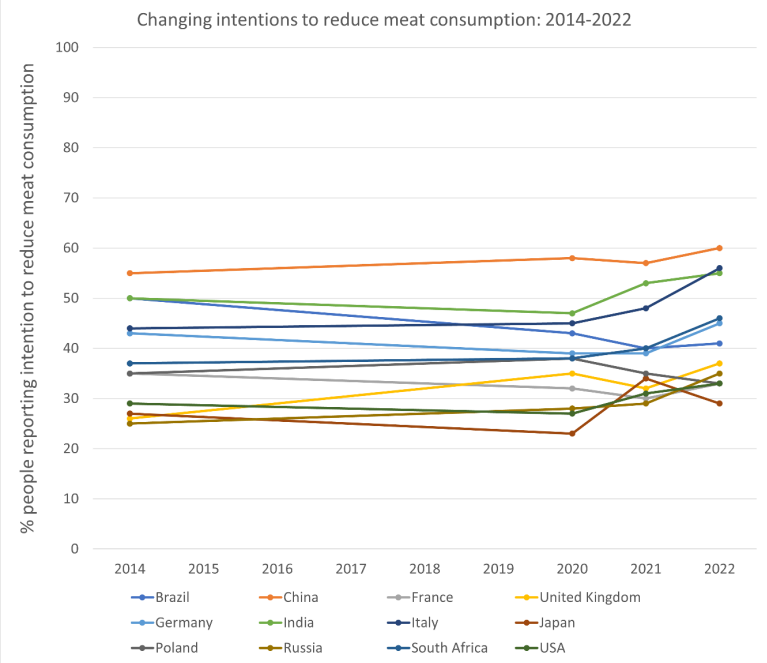


Figure 2. Changing intentions to reduce meat consumption in the period 2014-2022. Data are retrieved from the Ipsos 2020, 2021, and 2022 Earth Day reports and the 2014 dataset Climate Change & Diet by Ipsos and Chatham House (reported in Bailey et al., 2014).

Even though average global trends indicate that on average there is a trend towards increasing intentions to reduce meat consumption, not every country has a similar trajectory, with some countries notably also demonstrating a decrease in meat reduction intentions. Below, we examine in detail trends for five specific countries: the United Kingdom, Germany, the United States, Japan, and India.

United Kingdom: changing attitudes preceding behaviour change

Meat consumption in the UK has seen a decline in the period between 2008-2019, which has mostly been attributed to a reduction in portion size rather than changes in diet or the number of meat-eating days (Vonderschmidt et al., 2024). Awareness of the environmental impact of meat consumption is also relatively low in this period, with the percentage of people agreeing that meat production has a negative environmental impact being only 14% in 2007, increasing to 31% in 2017 (YouGov / Eating Better, 2017).

Attitudinal trends from the last decade (2014-2024) demonstrate increasingly favourable perceptions related to reducing meat consumption in the UK. For example, awareness of the environmental impact of meat production further increased to 41% in 2024 (up 10% from 2017) (Eating Better / Four Paws, 2024). The willingness to reduce meat consumption almost doubled

from 34% in 2014 to 61% in 2024 (Eating Better / Four Paws, 2024). The percentage of people who intend to eat less meat has also increased from 26% in 2014 to 37% in 2022 (Ipsos, 2022).

Yet, behaviour may be slower to change than people's attitudes and intentions. For example, the number of people who follow a flexitarian, vegetarian or vegan diet remained stable in the period between 2019-2025 around 20-24% of people (YouGov, 2025b). The number of people who say that they make the choice to reduce their meat consumption when shopping in the supermarket has also declined somewhat over the last 5 years (46% in 2019 to 37% in 2024 (YouGov, 2025a)).

Research on behaviour change suggests that changes in attitudes and intentions typically occur before changes in behaviour (e.g., Prochaska & Velicer, 1997). Moreover, because meat consumption is strongly influenced by prevailing social and cultural norms and contextual restraints (e.g., availability of vegetarian options), many scholars also assume a reduction in meat consumption will occur slowly and gradually, even if people privately already hold positive attitudes and intentions towards reducing meat consumption (e.g., Strassner & Hartmann, 2023; Verain et al., 2024).

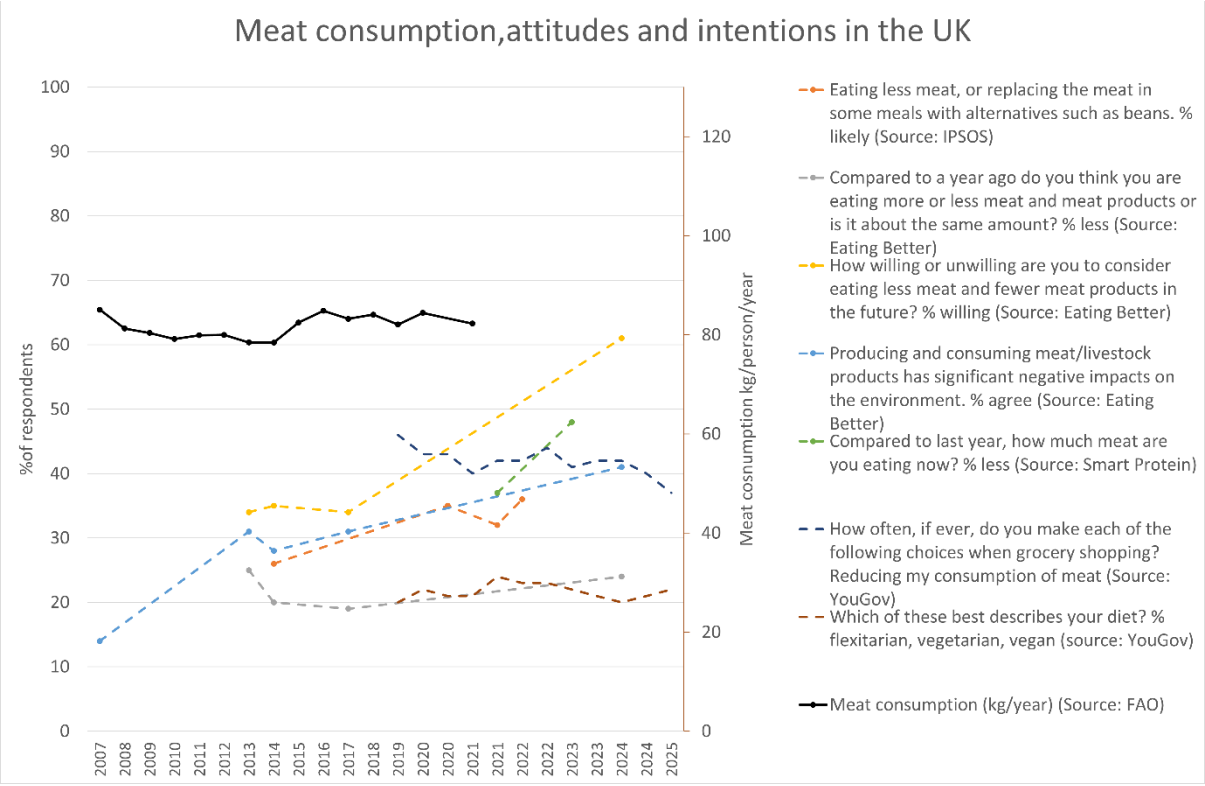


Figure 3. Actual meat consumption in the UK and results from various attitudinal surveys.

Germany: steady reductions following strong and stable intentions

Intentions to reduce meat consumption in Germany were already high in 2014, with 43% of respondents indicating they were likely to reduce their meat consumption (Bailey et al., 2014). Survey data from the Federal Ministry of Food and Agriculture indicates these intentions are followed by behaviours: the number of people who report eating meat everyday decreased steadily by more than 10 percentage points between 2016 and 2024 (BMEL, 2016, 2024). At the same time, the number of people who eat vegetarian or vegan alternatives doubled from 5% in 2019 to 10% in 2024 (BMEL, 2019, 2024). These trends also match actual meat consumption per capita, which is steadily declining. Further decreases in meat consumption may be expected in the future, as the number of people who report eating less meat than the year before still increased from 51% to 59% between 2021 and 2023 (Smart Protein, 2023).

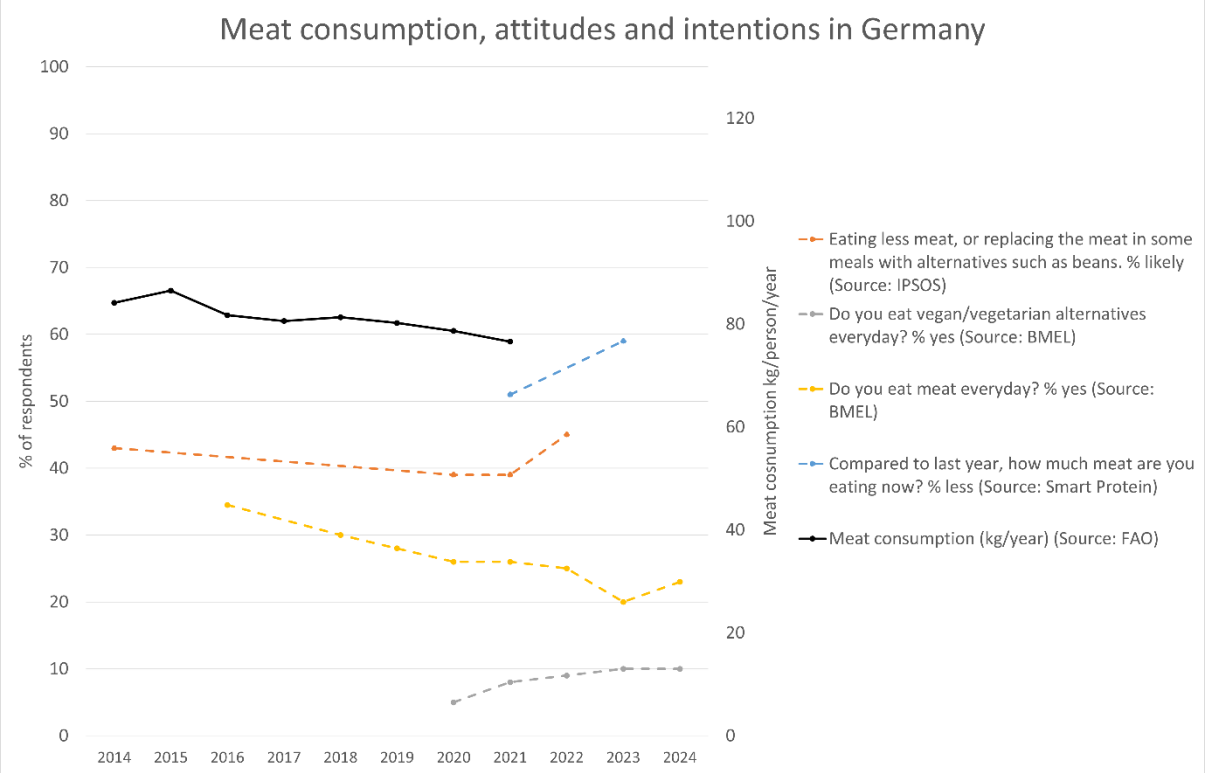


Figure 4. Actual meat consumption in Germany and results from various attitudinal surveys.

United States: meat consumption increasing, environmental concerns losing ground

Meat consumption in the United States reduced between 2007-2014, but starting increasing again in the period 2014-2021. This increase in meat consumption is coupled with a decrease in positive attitudes and intentions towards meat reduction. For example, the percentage of people that agree that people should consume less animal products reduced from 63% in 2017 to 56% in 2021 (Sentience Institute, 2021). The importance of environmental sustainability in food choices similarly peaked in 2016 (with 41% of people agreeing they find environmental sustainability

important), but declined over time, with a low of 27% in 2019 (IFIC, 2024). A recent study also concludes environmental considerations play a small role in influencing meat consumption in the US, as only 6% of respondents reduced their red meat consumption for environmental reasons, while the most often cited reasons for reducing meat consumption include health and price (Downs et al., 2024)

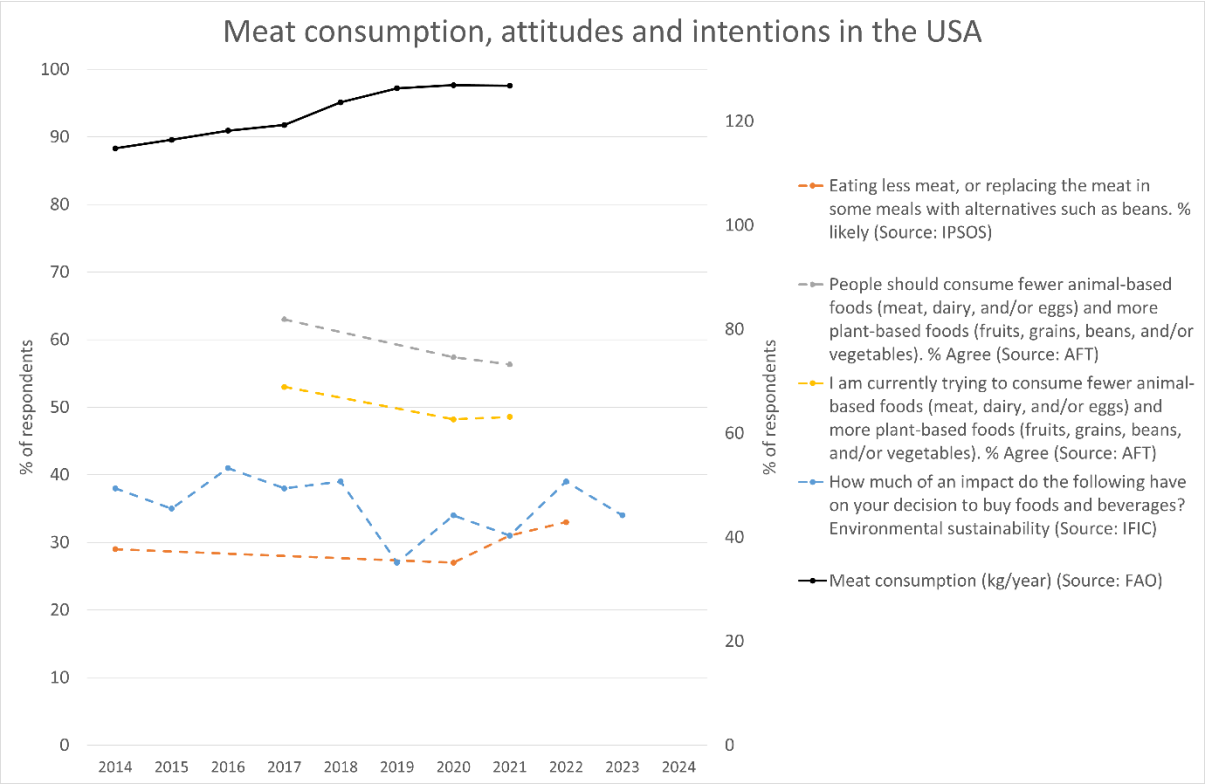


Figure 5. Actual meat consumption in the USA and results from various attitudinal surveys.

Japan: stable majority reluctant to reduce meat consumption

Intentions to reduce meat consumption in Japan are relatively low compared to other countries (27% in 2014), and also stable over time (29% in 2022) (Ipsos, 2022). Eating meat has only been a relatively recent addition to the Japanese diet, with meat consumption overtaking fish consumption only in 2007 (Sasaki et al., 2022). Meat consumption per capita in Japan is still relatively modest compared to other countries such as the US, Germany, and the UK, reducing the behavioural plasticity for this behaviour. Meat consumption also plays a less important role in determining households' carbon footprint, as meat consumption is relatively consistent across households (Kanemoto et al., 2019).

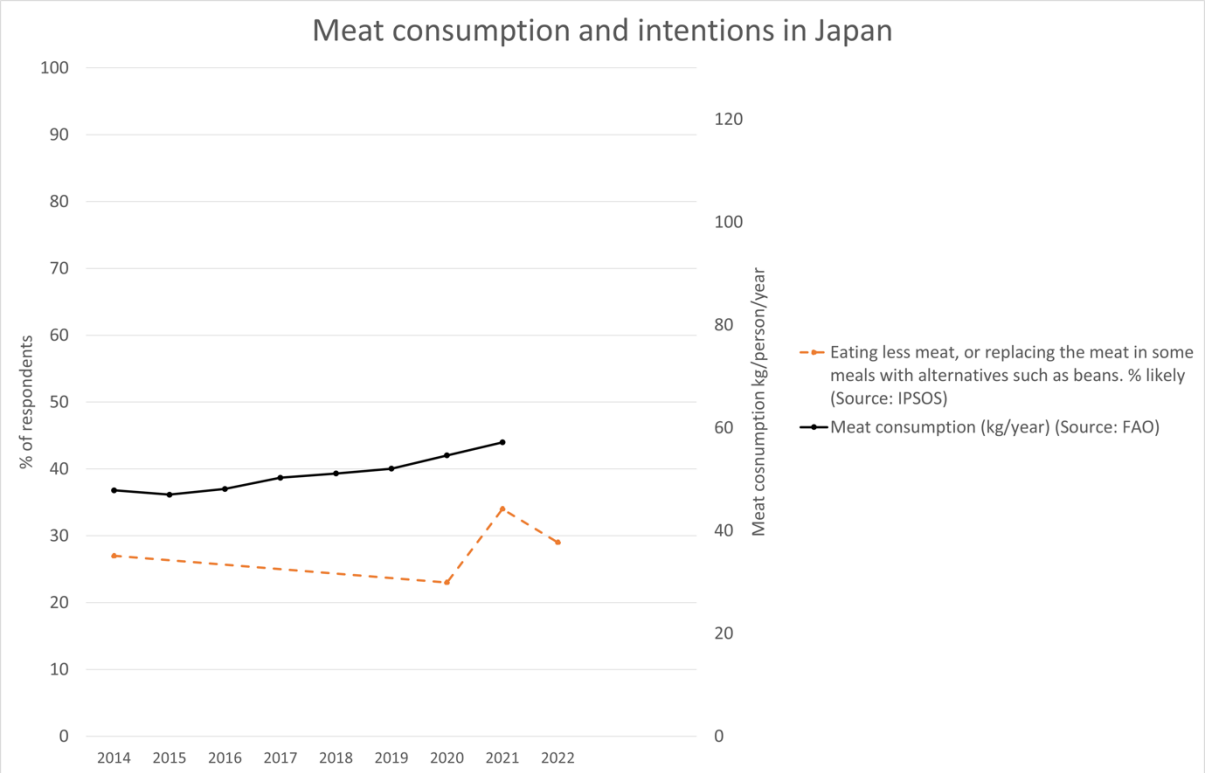


Figure 2. Actual meat consumption in Japan and results from IPSOS.

India: Consistent support for reducing meat consumption

Intentions to reduce meat consumption are consistently high in India, increasing from 50% in 2014 to 55% in 2022 (Ipsos, 2022). Cultural and religious influence make restrictions on meat consumption common among Indian adults, with 81% of adults indicating they observe some restrictions on eating meat (Pew Research Center, 2021). Such restrictions include following a vegetarian diet (39% of respondents) or not eating certain types of meat and/or avoiding meat consumption on certain days (41%) (Pew Research Center, 2021). Only 18% percent of people report no restrictions on meat consumption (Pew Research Center, 2021). Per capita meat consumption in India increases slightly in the period 2014-2022, but it still remains 13-fold lower than meat consumption in Germany, 14-fold lower than meat consumption in the UK, and 22-fold lower than meat consumption in the USA.

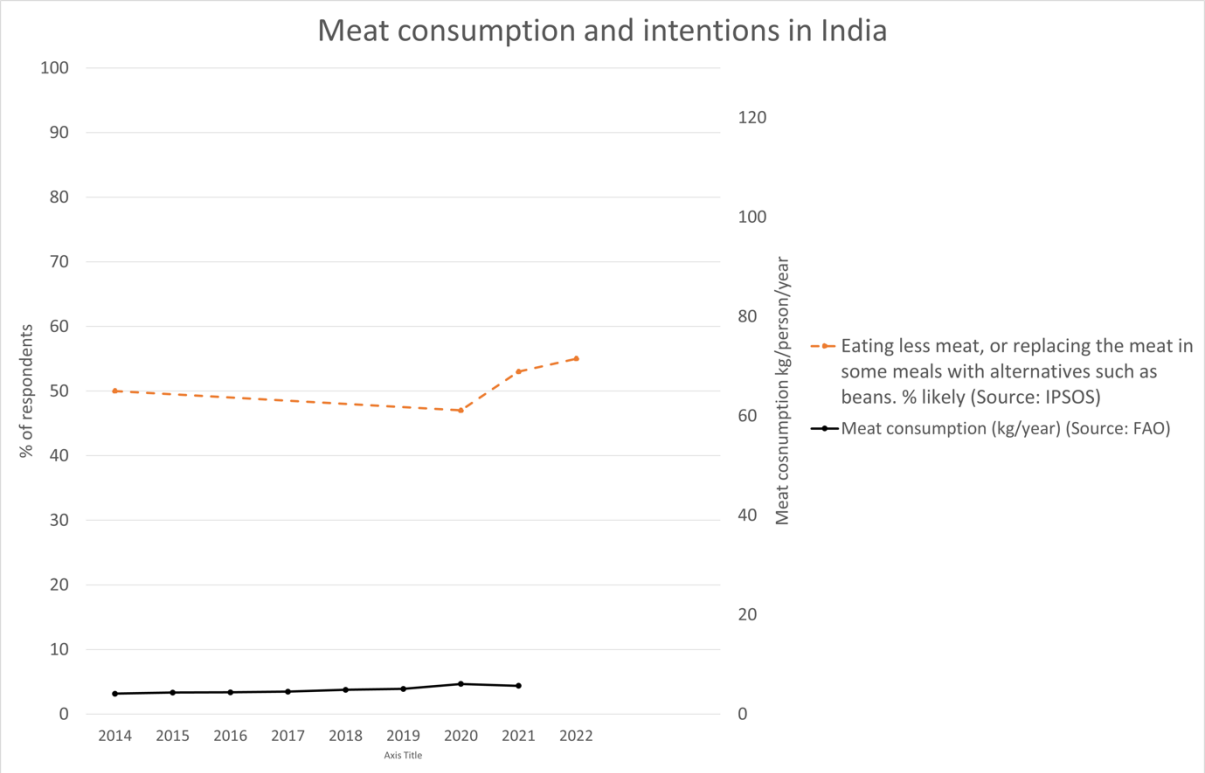


Figure 3. Actual meat consumption in India and results from IPSOS.

References for eating less meat case study.

Armitage, C. J., & Christian, J. (2003). From Attitudes to Behaviour: Basic and Applied Research on the Theory of Planned Behaviour. *Current Psychology: Developmental, Learning, Personality, Social*, *22*(3), 187-195.

Bailey, R., Froggatt, A., & Wellesley, L. (2014). *Livestock - Climate Change's Forgotten Sector. Global Public Opinion on Meat and Dairy Consumption*. https://www.chathamhouse.org/2014/12/livestock-climate-changes-forgotten-sector-global-public-opinion-meat-and-dairy-consumption

BMEL. (2016). Deutschland, wie es isst - Der BMEL-Ernährungsreport 2016. https://www.bmel.de/SharedDocs/Downloads/DE/_Ernaehrung/Ernaehrungsreport2016.html

BMEL. (2019). *Deutschland, wie es isst - der BMEL-Ernährungsreport 2019*. https://www.bmel.de/DE/themen/ernaehrung/ernaehrungsreport2019.html

BMEL. (2024). *Deutschland, wie es isst:Der BMEL-Ernährungsreport 2024*. https://www.bmel.de/DE/themen/ernaehrung/ernaehrungsreport2024.html

Downs, S. M., Merchant, E. V., Sackey, J., Fox, E. L., Davis, C., & Fanzo, J. (2024). Sustainability considerations are not influencing meat consumption in the US. *Appetite*, *203*, 107667. https://doi.org/10.1016/j.appet.2024.107667

Eating Better / Four Paws. (2024). *Public Attitudes Survey 2024*. https://www.eating-better.org/site/assets/files/10374/public_attitudes_survey_2024_final.pdf

IFIC. (2024). *2024 IFIC Food & Health Survey*. https://foodinsight.org/2024-food-health-survey/

Ipsos. (2020). Earth Day 2020: How does the world view climate

change and Covid-19? (Ipsos Global Advisor, Issue. https://www.ipsos.com/sites/default/files/ct/news/documents/2020-04/earth-day-2020-ipsos.pdf

Ipsos. (2021). Earth Day 2021: Public opinion and

action on climate

change (Ipsos Global Advisor, Issue. https://www.ipsos.com/sites/default/files/ct/news/documents/2021-04/Earth%20Day%202021.pdf

Ipsos. (2022). *Earth Day 2022: Public opinion on climate change* (Ipsos Global Advisor, Issue. https://www.ipsos.com/sites/default/files/ct/news/documents/2022-04/Ipsos%20-%20Global%20Advisor%20-%20Earth%20Day%202022%20-%20Release%201.pdf

Kanemoto, K., Moran, D., Shigetomi, Y., Reynolds, C., & Kondo, Y. (2019). Meat Consumption Does Not Explain Differences in Household Food Carbon Footprints in Japan. *One Earth*, *1*(4), 464-471. https://doi.org/10.1016/j.oneear.2019.12.004

Pew Research Center. (2021). *Religion in India: Tolerance and Segregation*. https://www.pewresearch.org/religion/2021/06/29/religion-and-food/

Prochaska, J. O., & Velicer, W. F. (1997). The transtheoretical model of health behavior change. *Am J Health Promot*, *12*(1), 38-48. https://doi.org/10.4278/0890-1171-12.1.38

Sasaki, K., Motoyama, M., Watanabe, G., & Nakajima, I. (2022). Meat consumption and consumer attitudes in Japan: An overview. *Meat Sci*, *192*, 108879. https://doi.org/10.1016/j.meatsci.2022.108879

Sentience Institute. (2021). Animals, Food, and Technology (AFT) Survey: 2021 Update. https://www.sentienceinstitute.org/aft-survey-2021

Smart Protein. (2023). Evolving appetites: an in-depth look at

European attitudes towards plant-based

eating. https://smartproteinproject.eu/european-attitudes-towards-plant-based-eating/

Strassner, A. M., & Hartmann, C. (2023). Gradual behaviour change towards meat reduction: Development and validation of a novel decisional balance scale. *Appetite*, *186*, 106537. https://doi.org/10.1016/j.appet.2023.106537

Verain, M. C. D., Reinders, M. J., Bouwman, E. P., & Dagevos, H. (2024). Gradual behaviour change towards meat reduction revisited: Applying the decisional balance scale in a Dutch study. *Appetite*, *203*, 107712. https://doi.org/10.1016/j.appet.2024.107712

Vonderschmidt, A., Jaacks, L. M., Alexander, P., Green, R., Bellows, A. L., & Stewart, C. (2024). Smaller meat portions contribute the most to reducing meat consumption in the United Kingdom. *Nat Food*, *5*(12), 982-987. https://doi.org/10.1038/s43016-024-01070-2

YouGov. (2025a). *Are Brits reducing their consumption of meat?* https://yougov.co.uk/topics/politics/trackers/are-brits-reducing-their-consumption-of-meat

YouGov. (2025b). *Dietary choices of Brits (e.g. vegeterian, flexitarian, meat-eater etc)?* https://yougov.co.uk/topics/society/trackers/dietery-choices-of-brits-eg-vegeterian-flexitarian-meat-eater-etc

YouGov / Eating Better. (2017). *YouGov / Eating Better Survey Results*. https://d25d2506sfb94s.cloudfront.net/cumulus_uploads/document/yjset7flxy/EatingBetterResults_170424_EatingLessMeat_W.pdf

Well with low: How do people expect sustainable lifestyles will affect their wellbeing?

Final version report 2025
Contribution from the University of Groningen, the Netherlands to EDITS (Energy Demand changes Induced by Technological and Social innovations) Project

by Chao Qin1*, Anne M. van Valkengoed1 & Linda Steg1

Submitted to
Research Institute of Innovative Technology for the Earth (RITE), Japan
and
the Ministry of Economy, Trade and Industry (METI), Japan

Abstract

This study aimed to examine how people evaluate the acceptability of supply and demand side strategies across three sectors: goods, transport, and heating. Moreover, we studied which factors predict acceptability of the strategies. A questionnaire study among 585 Dutch residents revealed that participants considered all strategies acceptable, but they preferred the demand side strategies more than the supply side strategies in the heating and transport sectors, while they preferred the supply side strategy more in the goods sector. The strategies were evaluated as more acceptable the more positive individuals' evaluation of the realism, affordability, fairness, effectiveness and quality of life impacts of the strategies. Participants who were more willing to change their lifestyle to combat climate change and who were more left/progressive leaning were more likely to have higher acceptability ratings. In addition, techno-optimistic participants were more likely to find transport sector strategies acceptable.

Energy and Water Use of Data Centers: A Comprehensive Review

Eric Masanet, University of California, Santa Barbara (UCSB)

Abstract

This study contributes to a comprehensive review of data center energy and water demand to be published in Volume 51 of the Annual Review of Environment and Resources (ARER) in collaboration with a team of authors from Lawrence Berkeley National Laboratory (USA) and Borderstep Institute (Germany). The UCSB contributions to this paper, which were conducted using EDITs funding, were specifically to inventory and assess the emerging policy landscape for regulating data center energy use and to review the data center energy-water nexus. Policy considerations are critical when conducting forward-looking analysis of the evolution of data center energy use, since policies may play a significant role in shaping future trajectories. This study identified and assessed 27 different data center policies at the local and national levels, resulting in a dataset of over 70 different policy attributes that may shape energy demand moving forward. Water demand considerations are important for considering potential siting decisions for future data center expansions, the energy use of cooling systems, and potential impacts on water availability and quality in consideration of Sustainable Development Goals. This study found that the current literature on data center water demand is sparse. This study reviewed and assessed the available estimates, with interpretations and guidance offered for analysts considering inclusion of water demand in future data center electricity demand scenarios, particularly as relates to artificial intelligence applications.

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)

28 February 2025

Submitted to

Research Institute of Innovative Technology for the Earth, Japan

IIASA Contract No. 24-131
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, and a summary of the Buildings Working Group activity.

Acknowledgements: EDITS is an initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA), and funded by Ministry of Economy, Trade, and Industry (METI), Japan.

Views or opinions expressed herein do not necessarily represent those of IIASA, its National Member Organizations or other organizations sponsoring the work.

Contents

PART 1. INTRODUCTION **3**

PART 2. CAPACITY BUILDING AND NETWORK **6**

EDITS MEMBERSHIP AND COLLABORATION 7
DEMAND-SIDE MODELS 8
COMMUNICATION AND ORGANIZATION 11
EDITS ANNUAL MEETING 2024 11

PART 3. RESEARCH AND MODELING **13**

RESEARCH HIGHLIGHTS 13
WORKING GROUPS 14
FAST-TRACK STREAMS 16
PUBLICATIONS 17

PART 4. BUILDINGS WORKING GROUP **21**

WG KEY DATA 21
WG ACTIVITIES IN 2024-25 23
SUCCESSES AND CHALLENGES 24

PART 5. OUTREACH **27**

ONLINE PRESENCE 27
POLICY AND PUBLIC ENGAGEMENT 27

PART 6. OUTLOOK FOR 2024-25 ..... ERROR! BOOKMARK NOT DEFINED.

ANNEX 1: EDITS ANNUAL CONFERENCE SUMMARY 32
ANNEX 2: EDITS ANNUAL CONFERENCE LIST OF PARTICIPANTS 35
ANNEX 3: EDITS ANNUAL AGENDA AND PROGRAM 40

Note: Links to EDITS documents are included in the text. Most of these have restricted access on the EDITS Sharepoint platform, because they are internal documents. Please, request access when prompted on the landing page.

PART 1. INTRODUCTION

This report provides an overview of the **fifth year of the "Energy Demand changes Induced by Technological and Social innovations (EDITS)" initiative.**

After an introduction, the report describes the EDITS set-up, working methods and research community building, reflecting on the changes implemented this year (Part 2). It is followed by reporting on the research and modeling work of the EDITS network between March 2023 to February 2024, specifically providing insights on the model complementarity exercise (MCE) and the fast-track achievements (Part 3). A specific report about the Working Group 1 – Buildings is included in PART 4. Then we explain the efforts on engagement and outreach during the period (Part 5).

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

EDITS has been moving away from stocktaking and describing the challenges towards innovation and filling in the identified gaps in the years 2023, 2024-25. This transition is continued in the coming years, leading to conceptual strengthening, scenario development and modeling, as well as broader-scale data collection.

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

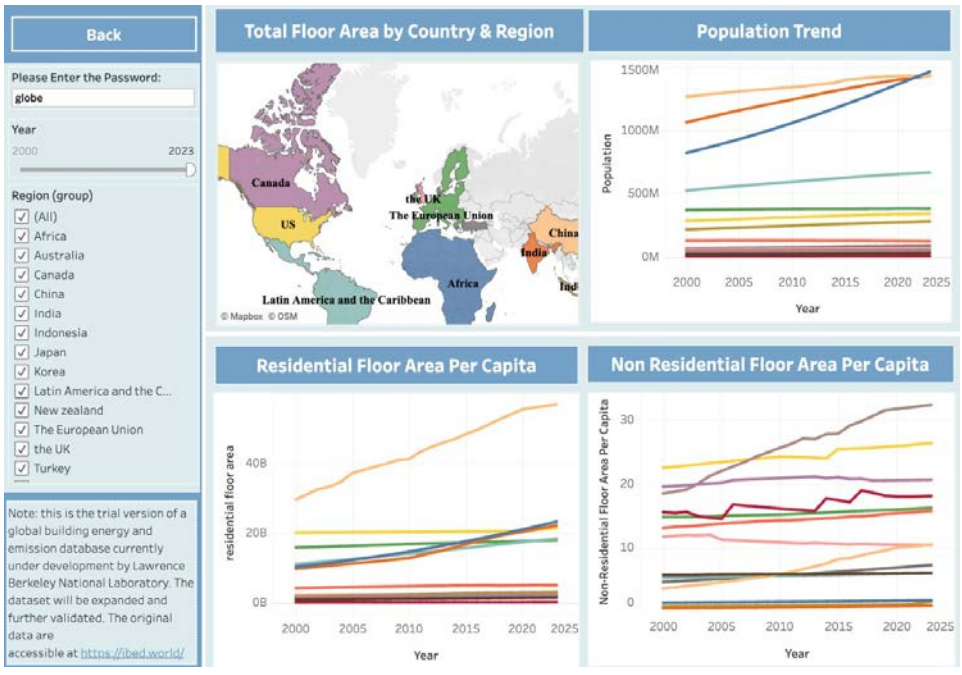
[1] Grubler et al. 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy 3 (6): 517-525.
[2] IPCC 2018. Global Warming of 1.5°C Special Report. URL: https://www.ipcc.ch/sr15/

scenario development and modelling. In 2023, the LED scenario narrative was updated with the "High with Low scenario narrative", which advocates putting wellbeing in the center of climate mitigation demand-side approach (link here).

The EDITS Community research directions were published in a commentary paper in Joule in January 2024, calling for (1) more diverse models and scenarios; (2) better data; (3) evidence on policies, societal actions, and business-models. Much of the activity in 2024-25 reflected these aspirations.

- **Reviews of low energy demand modeling in the demand sectors** (buildings, industry and transport) have been finalized. Relatedly, the paper on buildings models was published in ARER, similarly to the paper on industry models was published in ARER, and the transport model review paper was published in ERL.
- 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), 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 further developed: https://edits-project.sites.uu.nl and a **data dashboard** initiated (Table 1).
- Studies related to specific **demand-side data** are under way: (1) identifying data gaps, (2) costs and potentials of demand-side solutions, (3) cross-sectoral data.
- **Conceptual or wellbeing related papers** focused on social innovations (link), technological innovations (link) or both (link), and characteristics (link), and policy (link).
- The **model complementarity exercise (MCE)** is on-going for the transport sector. Three models participate (DNE21+, MESSAGE, and PASTA). After an attempt to collect low energy demand scenarios and find complementarity across them, we was found that scenario development is necessary to be able to link the relevant indicators. The focus has been placed on sharing mobility, and scenario development is currently on-going.

Table 1. Data dashboard prototype.



In 2024-25, the number of publications, presentations and public outreach programs has further increased[3]. The Community has published 36 new papers with direct acknowledgement of EDITS between March 2024 and

[3] The full list of publications, reports, outputs are included in Part 3 (Publications) of this report.

February 2025, which is more than double of the target. More than half of these (20) are direct outcomes of activities within EDITS, while the rest are papers that were catalyzed by discussions, collaborations and other ways from the network.

As of January 2025, the EDITS network has **191 individual members** from **24 countries** (Figure 5 in Part 2.) representing **102 Research Teams.** This is a small (but necessary) slow-down after a constant growth.

EDITS membership is by invitation only and free of charge. Members are free to choose their participation in the eight working groups (Figure 3) and other activities such as fast-tracks, hold webinars, invite members for other collaboration.

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 2).

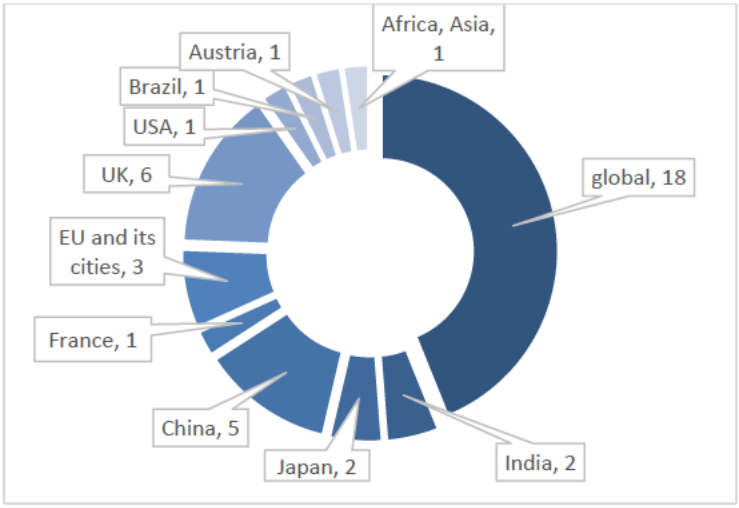


Figure 2. Coverage of the identified models within EDITS in 2024-25.

Intellectual and inspirational exchanges are organized in **Quarterly Meetings and an Annual Workshop**[4].
The Quarterlies were used to deliver updates about fast-track streams and updates about the IPCC process.
The Annual Meeting targeted the focal point of the EDITS Network, which is delivering research, data, scenarios for the IPCC process. Thus the main themes were selected as:

(1) developing strategies for IPCC and policy impact;
(2) strengthening demand-scenarios and progressing with the model complementarity,
(3) putting wellbeing in the center and improving the evidence base.

The EDITS 2024 Annual Meeting (Figure 9) took place between 8-10 October 2024 in Laxenburg, Austria, with the participation of over 50% of all the EDITS members and a few external invited experts.

Beyond the Consortium meetings, the EDITS network organized **over 60 specific meetings** in 2024-25, 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.).

[4] Part 2 of this report presents these meetings in more details.

PART 2. CAPACITY BUILDING AND NETWORK

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). IIASA coordinates the project with help of RITE, keeping administrative tasks, arrangement of meetings, and providing research leadership.

EDITS is a unique project that builds on bottom-up definition and formulation of research, collaborative identification of activities, remains largely informal without traditional project restraints. It connects members with similar interests, capitalizes on on-going activities, while adding value through exchange of knowledge, developing methodologies together, comparing and connecting modeling, scenarios, and analytical science. EDITS explores modeling innovations across demand-side models, extends scientific knowledge on demand-side-based transformation, as well as reaches out to policy and the general public to enhance the knowledge and appreciation of demand-side measures and solutions.

The organization of the network has a flexible structure (see Figure 4) with a **Plenary** that consists of all EDITS members. 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 keep regular contact with the whole community.

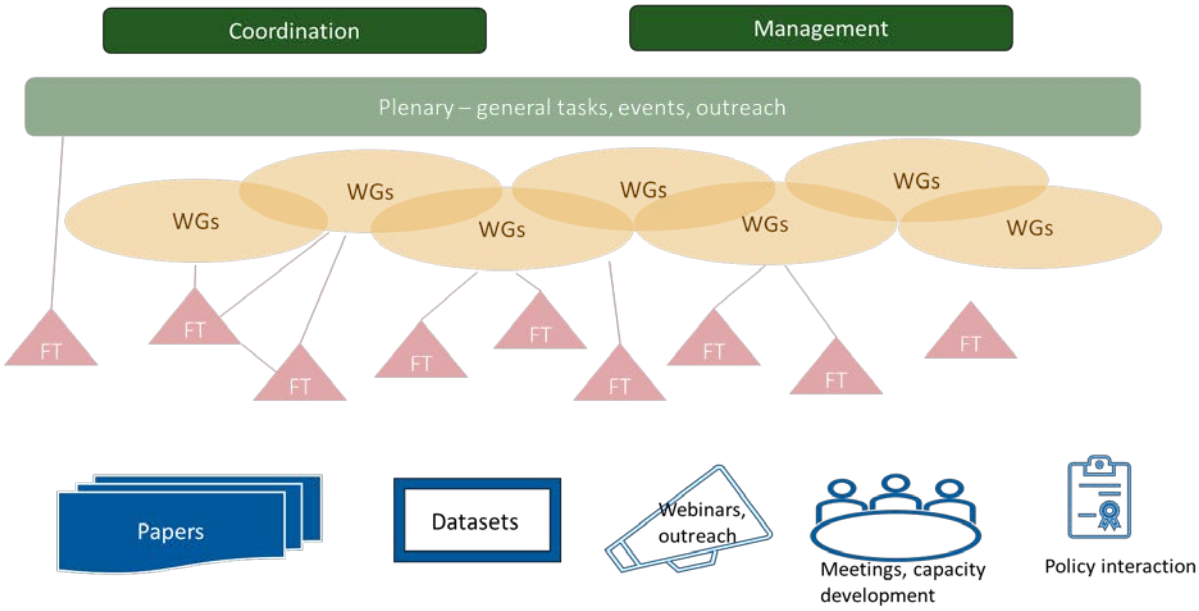


Figure 3. EDITS Network set-up and products. WG = working group, FT = fast-track stream

EDITS' work is organized into **eight working groups (WGs)**. This reflects the starting point of the EDITS research, functioning mostly as platforms for idea generation, which often lead to fast-track streams (FT) (see PART 3), small team work, outside projects or large-scale WG research. The latter is rare, but makes effort-heavy collaborative exercises, such as review papers and scenario collections. 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) (see PART 3 for more information). The fast-track scheme was launched in 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, delivering focused research or outreach results important for the demand-side research. 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 2024-25 five new fast-tracks were adopted beyond those eight from 2023 (Table 2).[5] More information on their activities are provided in PART 3.

Table 2. List of fast-tracks in 2023-24 and 2024-25 and their status

Fast-track number	status	Title	Lead
FT23-1	close to finish	High well-being with low energy demand: accounting for living standards in buildings modelling for the global south	Souran Chatterjee and Alessio Mastrucci
FT23-2	finished	Lower is Securer: Low Energy Demand and Energy Services Security	Nuno Bento, Arnulf Grübler, Benigna Boza-Kiss
FT23-3	close to finish	How much societal material stocks and resource use are needed to achieve Decent Living Standards and high wellbeing around the world?	Jan Streeck and Dominik Wiedenhofer
FT23-4	close to finish	New metrics to measure and value demand-side services and well-beings	Jingjing Zhang, Joyashree Roy
FT23-5	finished	Harnessing sufficiency	Yamina Saheb
FT23-6	on-going	Crises as opportunities for accelerating the demand side energy transition	Caroline Zimm
FT23-7	close to finish	Data gaps	Oreane Edelenbosch, Leila Niamir
FT23-8	finished	High with Low: Harnessing the Power of Demand-Side Solutions for High Wellbeing with Low Energy and Material Demand	Masa Sugiyama
FT24-1	on-going	WELL-with-LOW - Wellbeing Metrics and Assessment of LED-type Policy Options	Arnulf Grübler, Linda Steg and Anne van Valkengoed
FT24-2	on-going	Patterns of Diffusion in Social Innovations	Greg Nemet, Charlie Wilson
FT24-3	on-going	Method and Estimation of Cross-sectoral mitigation potential of Demand side solutions	Joyashree Roy, Leila Niamir
FT24-4	on-going	Decoding decent mobility: Relating needs, infrastructure, and energy use explicitly	Marlin Arnz, Zakia Soomauroo
FT24-5	on-going	More benefits with lower demand- Quantifying the co-benefits of LED scenarios	Souran Chatterjee

EDITS MEMBERSHIP AND COLLABORATION

As of February 2025, the EDITS network has **191 individual members** from **24 countries** (Figure 5) representing **102 Research Teams**. This is 5% growth from 181 members in 2024. EDITS membership is by invitation only. Members are 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

[5] More information about the results and activities are reported in Part 3.

Figure 4. 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**, which indicates a higher level commitment than being "only" a plenary member.

DEMAND-SIDE MODELS

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 2). 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 2024-25.

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 2024-25

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 5).

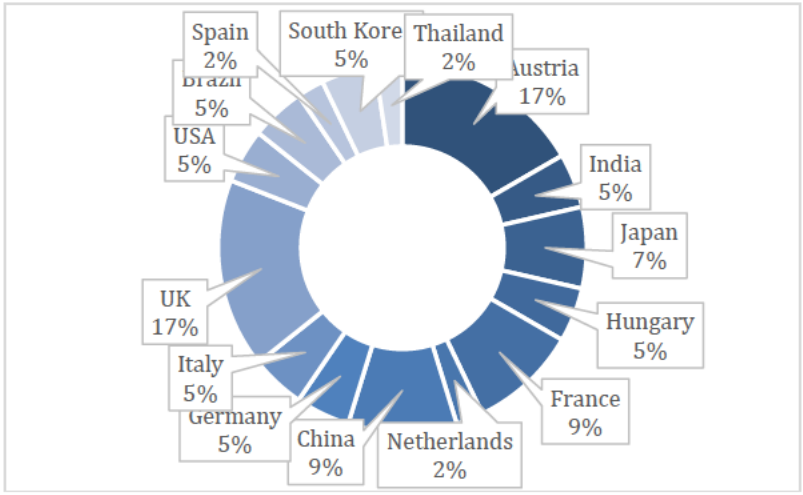


Figure 5. Host countries of the identified models within EDITS in 2023-24.

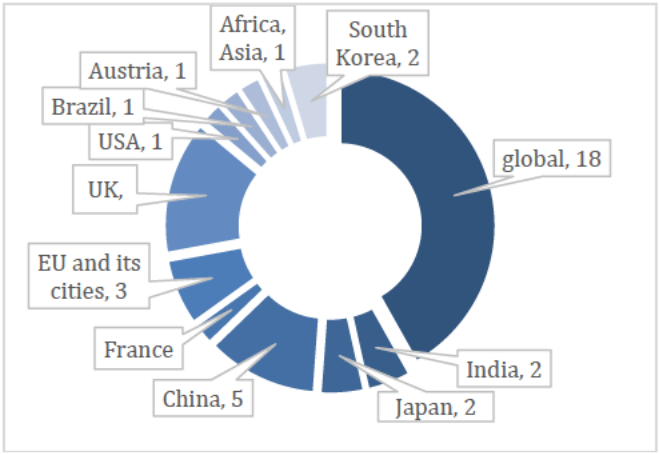


Figure 6. Coverage of the identified models within EDITS in 2023-24.

COMMUNICATION AND ORGANIZATION

Daily communication: 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 5). There is a public email for external interest: edits-public@iiasa.ac.at.

Documents and filing: 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.

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. A Community on **Zenodo**[6] was established, where all dataset from EDITS can be collected: https://zenodo.org/communities/edits/ , for example the supplementary data from the paper Bento et al. 2024.

A central repository for papers and presentations is created in the online tool **Zotero** at https://www.zotero.org/groups/4567109/edits-general/library , as well as a list is curated on the Sharepoint.

Regular meetings: Intellectual and inspirational exchanges are organized in **Quarterly Meetings**. In 2024-25, **two Quarterly meetings (5-6 March and 4-5 June)** were organized.

Quarterly 2024/1 was held on 5-6 March (79 participants). The meeting reviewed the progress by all 2023 fast-tracks and introduced the new winner. The slides and agenda can be found here: 2024 - Quarterly 2024.1.

Quarterly 2024/2, was held on 4-5 June (62 participants). New fast-tracks reported on their progress, and comments were received from the Community. The second session was dedicated to a scenario development Austrian project, NetZero2040 (find out more: https://www.netzero2040.at/). The slides and agenda can be found here: 2024 - Quarterly 2024.2.

These meetings are addressed at the whole EDITS Network. Beyond the Consortium meetings, the EDITS network organized **over 60 specific meetings** in 2024-25, 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.).

EDITS ANNUAL MEETING 2024

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.

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, titled "Energy demand changes through innovations";
- in August 2022 in Laxenburg, Austria, titled "Transformation to high wellbeing with low energy demand";
- in November 2023 in Lisbon, Portugal, titled "Conference on improving wellbeing while avoiding dangerous climate change"; and finally
- in October 2024 in Laxenburg, Austria, titled "High with Low scenarios towards AR7"

[6] https://zenodo.org/, Key benefits: run by CERN's Data Centre; promotes Open Science; uploads are assigned a DOI); available version control; GitHub integration.

The EDITS 2024 Annual Meeting (Figure 9) took place between 8-10 October 2024 in Laxenburg, Austria, with the participation of over 50% of all the EDITS members and a few external invited experts. There was a possibility to join online.

Building on the current focus areas of EDITS, three key themes were selected for the meeting:

(1) developing strategies for IPCC and policy impact;
(2) strengthening demand-scenarios and progressing with the model complementarity,
(3) putting wellbeing in the center and improving the evidence base.

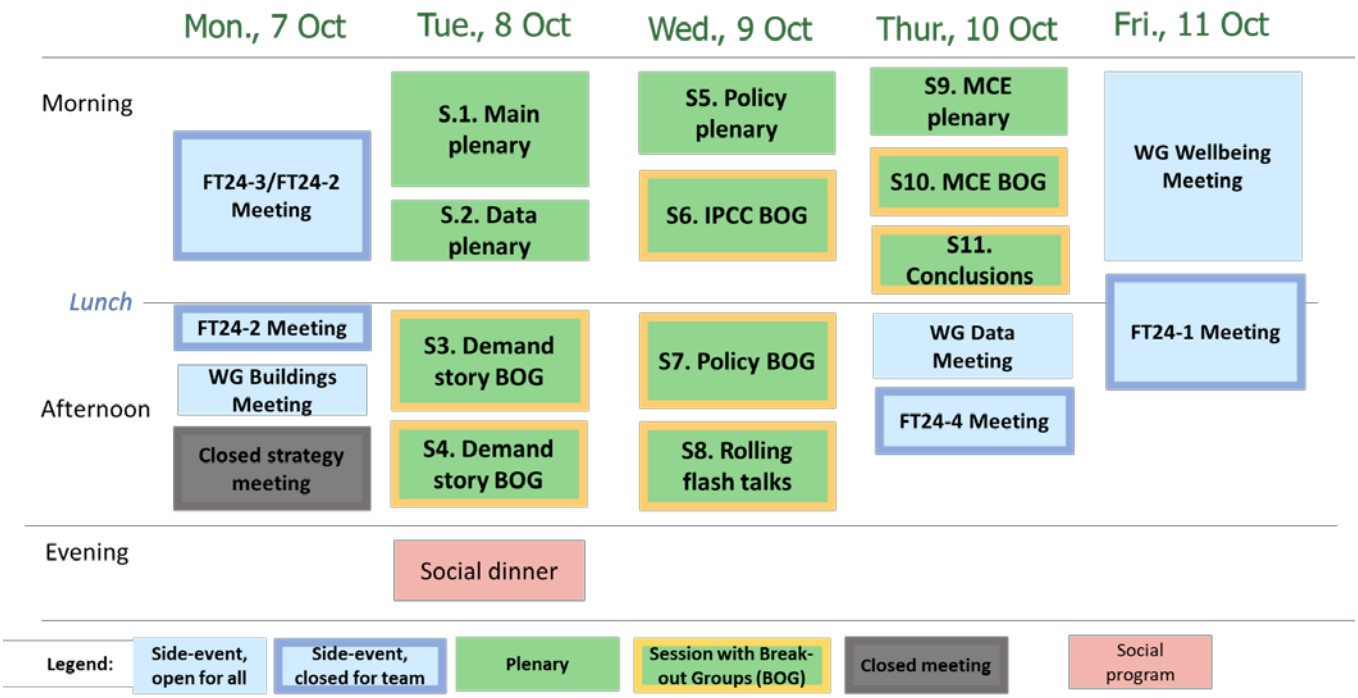


Figure 7. Overview of the core part of Annual Conference program

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 Buildings, WG Data and WG Wellbeing.
- Fast-track streams arranged practical meetings, where they discussed particularities of their submitted papers or to progress on writing and data collections.

Key figures

The meeting had **96 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 **89 participants were present in-person and 7 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:

A summary of the Meeting is included in a separate report, 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).

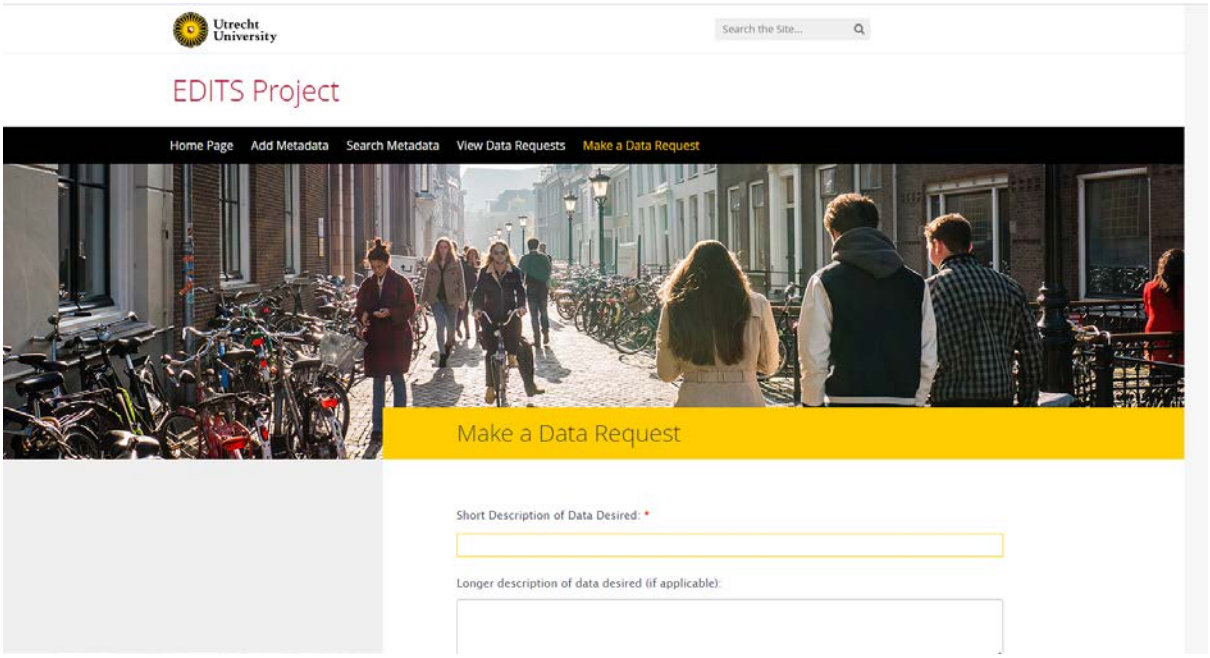


Figure 8. Metadatabase

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 activity is presented (Table 5).

Table 5. EDITS Working Groups

Working Group	Co-lead		Group email address	Main activities in 2024-25
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 have operated since 2023 are shown in Table 6. Three (FT23-2, FT23-5, FT23-8) have been fully closed with papers published. Two have completed one paper publication, however proceed to write a second paper. All others are close to completion.

Table 6. List of fast-tracks and their results and expected further work.

Fast-track number	Title	Results and outputs
FT23-1	High well-being with low energy demand: accounting for living standards in buildings modelling for the global south	✓ Paper 1 (methods): published, November 2024 https://doi.org/10.1016/j.erss.2024.103757 (✓) Paper 2 (scenario): submission 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	✓ Perspective paper – published 29 Feb. 2024, 10.1126/science.adj6150 ✓ Public webinar held in June 2024 ✓ Dataset in Zenodo ✓ 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?	✓ Scientific paper: submitted, under review https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5111257
FT23-4	New metrics to measure and value demand-side services and well-beings	(✓) Scientific paper: submitted, but rejected, new journal is sought ✓ Datasets
FT23-5	Harnessing sufficiency	✓ Scientific paper: published, December 2024, https://doi.org/10.1016/j.erss.2024.103813 X Policy brief + public webinar
FT23-6	Crises as opportunities for accelerating the demand side energy transition	* Perspective paper: draft
FT23-7	Data gaps	(✓) Scientific paper: to be submitted in March 2025
FT23-8	High with Low: Harnessing the Power of Demand-Side Solutions for High Wellbeing with Low Energy and Material Demand	✓ Perspective paper: published 11. Jan. 2024, 10.1016/j.joule.2023.12.014
FT24-1	WELL-with-LOW - Wellbeing Metrics and Assessment of LED-type Policy Options	✓ Dataset completed (✓) Survey in one country completed, 2 more to do (✓) Paper drafted, to be completed and submitted ca. May 2025
FT24-2	Patterns of Diffusion in Social Innovations	✓ Dataset completed (✓) Paper drafted, to be completed and submitted ca. May 2025
FT24-3	Method and Estimation of Cross-sectoral mitigation potential of Demand side solutions	✓ Dataset completed (✓) Paper drafted, to be completed and submitted ca. May 2025
FT24-4	Decoding decent mobility: Relating needs, infrastructure, and energy use explicitly	✓ Modeling completed (✓) Paper 1 ready, submitted * Paper 2 to be completed
FT24-5	More benefits with lower demand- Quantifying the co-benefits of LED scenarios	✓ Dataset completed (✓) Paper drafted, to be completed and submitted ca. May 2025

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 and 2024, a new set will be selected during March 2025.

PUBLICATIONS

During the 2024-25 period, the Community has **published 36 new papers with direct acknowledgement of EDITS, which is more than double of the target**. A **further 10 papers have been submitted** to journals and are under review, and **nine more are in draft status** and will be soon submitted for publication. This is a significant growth over the last years.

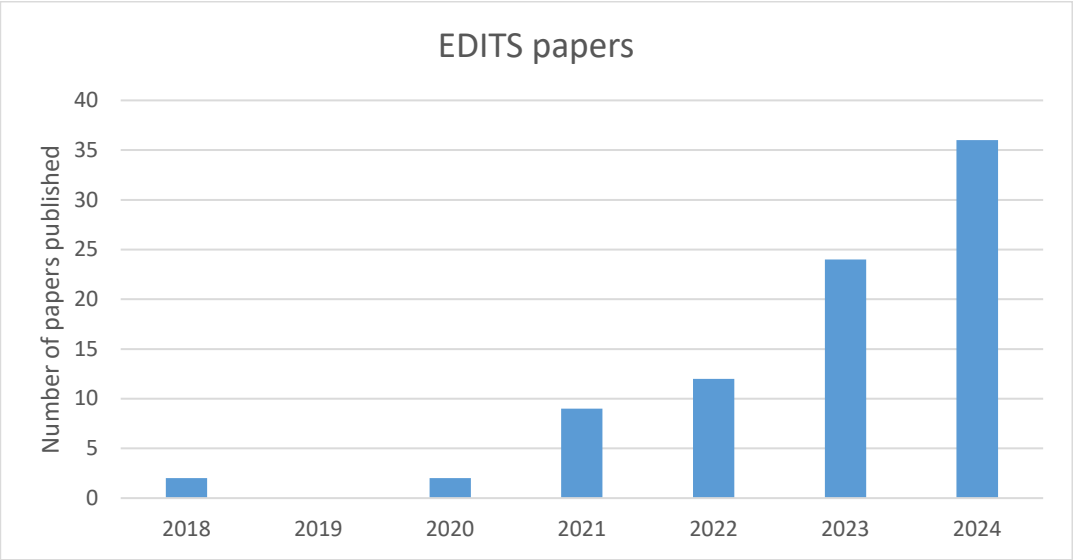


Figure 9. Number of published EDITS papers that originate directly from the work within EDITS

The list of publications directly acknowledging EDITS (note that papers published in January-February 2024 are not listed, because they were reported in the previous year):

1. Bento, Nuno, Alejandro Nuñez-Jimenez, and Noah Kittner. 2025. "Decline Processes in Technological Innovation Systems: Lessons from Energy Technologies." *Research Policy* 54 (3): 105174. https://doi.org/10.1016/j.respol.2025.105174.
2. Bonan, J., C. Cattaneo, G. d'Adda, A. Galliera, and M. Tavoni. 2024. "Widening the Scope: The Direct and Spillover Effects of Nudging Water Efficiency in the Presence of Other Behavioral Interventions." *Journal of Environmental Economics and Management* 127 (September):103037. https://doi.org/10.1016/j.jeem.2024.103037.
3. Bonan, Jacopo, Cristina Cattaneo, Giovanna d'Adda, and Massimo Tavoni. 2024. "Heat of the Moment: How Temperature Influences the Search and Purchase of Energy-Using Appliances." *Journal of Economic Behavior & Organization* 227 (November):106703. https://doi.org/10.1016/j.jebo.2024.106703.
4. Bonan, J., C. Cattaneo, G. d'Adda, A. Galliera, and M. Tavoni. 2025. "Social Norms and Tariff Salience: An Experimental Study on Household Waste Management." Journal of Environmental Economics and Management 130 (March):103124. https://doi.org/10.1016/j.jeem.2025.103124 .
5. Chatterjee, Joyee Shairee, Sirayuth Thongprasert, and Shreya Some. 2024. "Communication, Climate Mitigation, and Behavior Change Interventions: Understanding Message Design and Digital Media Technologies." *Annual Review of Environment and Resources* 49 (1): 655–72. https://doi.org/10.1146/annurev-environ-121322-070317.
6. Chatterjee, Souran, Alessio Mastrucci, Leila Niamir, Kaveri Ashok, Ashok Sreenivas, Srihari Dukkipati, Vassilis Daioglou, et al. 2024. "Balancing Energy Transition: Assessing Decent Living Standards and Future Energy Demand in the Global South." *Energy Research & Social Science* 118 (December):103757. https://doi.org/10.1016/j.erss.2024.103757.

7. Chatterjee, Souran, Gergely Molnár, Benedek Kiss, Daniel Topál, and Diana Ürge-Vorsatz. 2025. "Navigating the Transition: Modelling the Path for Net-Zero European Building Sector." *Renewable and Sustainable Energy Reviews* 207 (January):114827. https://doi.org/10.1016/j.rser.2024.114827.

8. Costa, Paulo Moisés, António Duarte, Paulo Tomé, Nuno Bento, and Margarida Fontes. 2024. "Technological Innovations in Decarbonisation Strategies: A Text-Mining Approach to Technological Readiness and Potential." *Energies* 17 (24): 6479. https://doi.org/10.3390/en17246479.

9. Creutzig, Felix, Joyashree Roy, and Jan Minx. 2024. "Demand-Side Climate Change Mitigation: Where Do We Stand and Where Do We Go?" *Environmental Research Letters* 19 (4): 040201. https://doi.org/10.1088/1748-9326/ad33d3.

10. Creutzig, Felix, Alexander Schmaus, Eva Ayaragarnchanakul, Sophia Becker, Giacomo Falchetta, Jiawei Hu, Mirko Goletz, et al. 2024. "Shared Pooled Mobility: Expert Review from Nine Disciplines and Implications for an Emerging Transdisciplinary Research Agenda." *Environmental Research Letters* 19 (5): 053004. https://doi.org/10.1088/1748-9326/ad3cf5.

11. Creutzig, Felix, Sofia G. Simoes, Sina Leipold, Peter Berrill, Isabel Azevedo, Oreane Edelenbosch, Tomer Fishman, et al. 2024. "Demand-Side Strategies Key for Mitigating Material Impacts of Energy Transitions." *Nature Climate Change* 14 (6): 561–72. https://doi.org/10.1038/s41558-024-02016-z.

12. Ita, Sayaka, Ayu Washizu, and Yiyi Ju. 2024. "Lifestyle Changes Overweighing Technology Improvement in Household Decarbonization: Evidence from Japan during 1990-2020." *Carbon Footprints* 3 (4). https://doi.org/10.20517/cf.2024.30.

13. Kramel, Diogo, Volker Krey, Oliver Fricko, Florian Maczek, Helene Muri, and Anders Strømman. 2024. "Maritime Sector Transition Pathways towards Net-Zero within Global Energy Scenarios." https://doi.org/10.21203/rs.3.rs-4471628/v1.

14. Martinez, Luis M., John P. Pritchard, and Philippe Crist. 2024. "Shared Mobility's Role in Sustainable Mobility: Past, Present, and Future." *Annual Review of Environment and Resources* 49 (1): 191–222. https://doi.org/10.1146/annurev-environ-121522-041916.

15. Martinez, Luis Miguel G., and John P. Pritchard. 2024. "Modelling Global Freight Decarbonisation Pathways." https://doi.org/10.21203/rs.3.rs-4091812/v1.

16. Masanet, Eric, Nuoa Lei, and Jonathan Koomey. 2024. "To Better Understand AI's Growing Energy Use, Analysts Need a Data Revolution." *Joule* 8 (9): 2427–36. https://doi.org/10.1016/j.joule.2024.07.018.

17. Millward-Hopkins, Joel, Yamina Saheb, and Jason Hickel. 2024. "Large Inequalities in Climate Mitigation Scenarios Are Not Supported by Theories of Distributive Justice." *Energy Research & Social Science* 118 (December):103813. https://doi.org/10.1016/j.erss.2024.103813.

18. Millward-Hopkins, Joel, and Vivien Fisch-Romito. 2025. "We Have to Talk about Overconsumption (in Three Different Ways)." *Environmental Research Letters* 20 (3): 031007. https://doi.org/10.1088/1748-9326/adb986.

19. Mohanty, Parimita, Indrajit Pal, and Joyashree Roy. 2024. "Improving Community Resilience through Distributed Solar Energy as Critical Infrastructure – a Case Study of South Asia." *International Journal of Disaster Resilience in the Built Environment*, May. https://doi.org/10.1108/IJDRBE-02-2023-0039.

20. Niamir, Leila, Alessio Mastrucci, and Bas Van Ruijven. 2024. "Energizing Building Renovation: Unraveling the Dynamic Interplay of Building Stock Evolution, Individual Behaviour, and Social Norms." *Energy Research & Social Science* 110 (April):103445. https://doi.org/10.1016/j.erss.2024.103445.

21. Niamir, Leila, and Elke U. Weber. 2024. "What Can We Do About the Climate Crisis?" *Frontiers for Young Minds* 12 (September):1421602. https://doi.org/10.3389/frym.2024.1421602.

22. Nick, Sascha. 2024. “Systems Perspectives on Transforming Swiss Housing by 2040: Wellbeing, Shared Spaces, Sufficiency, and de-Sprawl.” *Front. Sustain.* 5 (July):1375271. https://doi.org/doi.org/10.3389/frsus.2024.1375271.

23. Pachauri, Shonali, Olivia Coldrey, Giacomo Falchetta, and Setu Pelz. 2024. “Innovation in Distributed Energy Services for Sustainable Development: Case Studies from Sub-Saharan Africa.” *Environmental Research Letters* 19 (11): 114090. https://doi.org/10.1088/1748-9326/ad8460.

24. Pauliuk, Stefan. 2024. “Decent Living Standards, Prosperity, and Excessive Consumption in the Lorenz Curve.” *Ecological Economics* 220 (June):108161. https://doi.org/10.1016/j.ecolecon.2024.108161.

25. Pauliuk, Stefan, Fabio Carrer, Niko Heeren, and Edgar G. Hertwich. 2024. “Scenario Analysis of Supply- and Demand-side Solutions for Circular Economy and Climate Change Mitigation in the Global Building Sector.” *Journal of Industrial Ecology* 28 (6): 1699–1715. https://doi.org/10.1111/jiec.13557.

26. Pettifor, Hazel, Maureen Agnew, Charlie Wilson, and Leila Niamir. 2024. “Disentangling the Carbon Emissions Impact of Digital Consumer Innovations.” *Journal of Cleaner Production* 485 (December):144412. https://doi.org/10.1016/j.jclepro.2024.144412.

27. Ren, Lei, Hong Shi, Yifang Yang, Jianzhe Liu, and Xunmin Ou. 2025. “Carbon Reduction Cost of Hydrogen Steelmaking Technology in China.” *Energy* 320 (April):135177. https://doi.org/10.1016/j.energy.2025.135177.

28. Santos, Alberto, Pedro Maia, Rodrigo Jacob, Huang Wei, Camila Callegari, Ana Carolina Oliveira Fiorini, Roberto Schaeffer, and Alexandre Szklo. 2024. “Road Conditions and Driving Patterns on Fuel Usage: Lessons from an Emerging Economy.” *Energy* 295 (May):130979. https://doi.org/10.1016/j.energy.2024.130979.

29. Shimoda, Yoshiyuki. 2025. “The Role of Building Performance Simulations in Citywide and National Global Warming Mitigation Policy.” *Journal of Building Performance Simulation* 18 (1): 93–98. https://doi.org/10.1080/19401493.2024.2421327.

30. Thomas, Hugh, Luis Gabriel Carmona Aparicio, Felix Creutzig, Takuya Hara, Ayami Hayashi, Camila Ludovique, Luis M Martinez, et al. 2024. “Models and Methods for Transport Demand and Decarbonisation: A Review.” *Environmental Research Letters* 19 (9): 093005. https://doi.org/10.1088/1748-9326/ad6b3a.

31. Ürge-Vorsatz, Diana, Souran Chatterjee, Luisa F. Cabeza, and Gergely Molnár. 2025. “Global and Regional Estimation and Evaluation of Suitable Roof Area for Solar and Green Roof Applications.” Developments in the Built Environment 21 (March):100607. https://doi.org/10.1016/j.dibe.2025.100607 .

32. Wei, Huang, Camila Callegari, Ana Carolina Oliveira Fiorini, Roberto Schaeffer, and Alexandre Szklo. 2024. “Technical and Economic Modelling of Last-Mile Transport: A Case for Brazil.” *Case Studies on Transport Policy* 16 (June):101219. https://doi.org/10.1016/j.cstp.2024.101219.

33. Wiedenhofer, Dominik, Jan Streeck, Frauke Wiese, Elena Verdolini, Alessio Mastrucci, Yiyi Ju, Benigna Boza-Kiss, et al. 2024. “Industry Transformations for High Service Provisioning with Lower Energy and Material Demand: A Review of Models and Scenarios.” *Annual Review of Environment and Resources* 49 (1): 249–79. https://doi.org/10.1146/annurev-environ-110822-044428.

34. Wiese, Frauke, Carina Zell-Ziegler, Celia Burghardt, Yannick Kloos, and Mirko Schäfer. 2024. “Reducing Demand: A Quantitative Analysis of Energy Service Demand Indicators in Sufficiency-Oriented Scenarios.” *Environmental Research Communications* 6 (12): 121003. https://doi.org/10.1088/2515-7620/ad966e.

35. Wilson, Charlie, Theodoros Arvanitopoulos, Simon Schaub, Andrew Jordan, Jale Tosun, and Nicholas Vasilakos. 2024. “Climate Policy Portfolios That Accelerate Emission Reductions.” https://doi.org/10.21203/rs.3.rs-4742975/v1.

36. Zhang, Jingjing, Michelle Johnson-Wang, Nina Khanna, Max Wei, Bianka Shoai-Tehrani, and Nan Zhou. 2025. “Energy Sufficiency for Deep Decarbonization: A Modeling Framework.” *Nexus* 2 (1): 100055. https://doi.org/10.1016/j.ynexs.2025.100055.

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).*

PART 4. Buildings Working Group

The **Working Group (WG) on Buildings** is one of the eight WGs within the foundational structure of the EDITS network. The WG is led exclusively by IIASA, and therefore reporting is included in the current document.

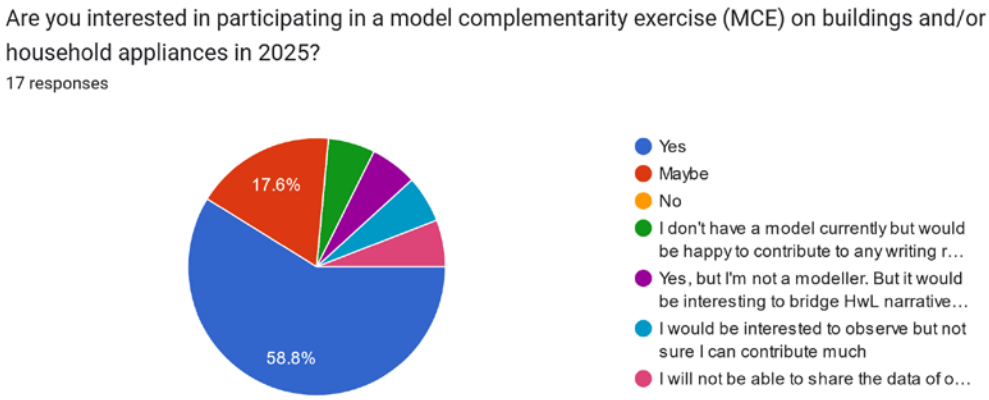
Buildings protect wellbeing and support human activities by providing shelter and services to their tenants and owners. Improving service provision in buildings while reducing energy demands is important for climate mitigation and many UN Sustainable Development Goals (SDGs). The built environment is made up of integrated components (i.e. housing, personal and freight transport, infrastructure, urban green and land), while also interacting with people's activities, decisions, choices. EDITS' WG Buildings has been active since 2020 mainly focused on the building sector as a whole, and has extended its focus to the urban level.

WG KEY DATA

- **Co-leads:** Alessio Mastrucci and Leila Niamir
- **WG members:** 82 (as of January 2025), see
- **Main overall goals:**
    - Identify gaps and expand knowledge in building sector modelling towards representing social, technological, and structural transformation;
    - Identify, prioritize and establish collaborations within and beyond the building sector, in particular with EDITS WG2-Data and EDITS WG3-Protocol to enhance data availability and to establish modelling protocols respectively, as well as with other sectoral WGs on cross-sectoral linkages;
    - Contribute to and support EDITS activities, e.g. fast-track projects, related to the topics of this WG, and promote dissemination of results.
- **Methods of the WG:**
    - Model comparisons and model complementarity projects;
    - Surveys on building sector models and data collection from models;
    - Data collection and modelling protocols and templates;
    - Facilitating brainstorming and discussion sessions on WG-related topics;
    - Disseminate results: journal publications, conference activities, workshops, and webinars.
- **Starting point:** Review paper published in November 2023 https://doi.org/10.1146/annurev-environ-112321-102921
- **Meetings in the financial year 2024-25:**
  In the current reporting period meetings were concentrated in dedicated working teams, and linking across WGs and other streams.

  The main WG meeting took place on 7 October 2024, Monday in person as a side-event of the Annual Meeting.

  This meeting was attended by 31 participants.
  The presentation slides can be accessed from the EDITS sharepoint at: EDITS2024_WGBuildings_20241007.pptx.
    - The meeting started with an introduction of the aims of the meeting. The Working Group has published a model review paper (see above), collected data, hosted and collaborated with fast-track steams (see below), in particular related to HwL scenario development in India, and analysis of security and wellbeing aspects of HwL futures in the UK and India.
    - The WG will move towards scenario collection and development, and this year has been used to prepare a protocol development (in collaboration with WG Protocol) and collection of already existing scenarios as well as interest to work on these.
    - A survey was conducted before the meeting that showed that 60% of relevant WG members have an interest to actively participate in the MCE on buildings in 2025, 18% might be interested, and almost all others would serve as support or observers, e.g. because they have no models.



- The WG hosts various model-types, but has low/no representation of socio-behavioural dimension
  - IAM-Sectoral models (IMAGE, MESSAGE, EDGE)
  - Sectoral models (HEB (Global), CBEEM (China), SAFARI (India), TREES (Japan))
  - Industrial ecology/Materials (RECC, MISO2, Materials-GRoWL, RASMI)
- About a third of the models already have a LED or HwL scenario that can be used for the MCE. These are: IMAGE (Global, India,...), MESSAGE (Global,India, EU,...), HEB (Global, India, EU,...), RECC (LATAM), CBEEM (China), SAFARI (India)
- Knowledge and experience about using the IPCC data formats and variables are limited. It has been agreed that training will be needed to strengthen the technical knowledge. Such a training can be provided by IIASA and a first session has already been presented at the second Quarterly in 2023.
- The scope of such an MCE that could be feasible for participants was also asked in the survey. Geographically global scope, mostly in the residential subdomain, focusing on low energy demand, low material demand, decent living standards, sufficiency, behavioural aspects, technological efficiency are at high interests.
- The participants agreed that a larger scale MCE is desirable for most WG members and should be carried out as a core WG activity (i.e. not as a fast-track or sub-team effort). Other topics (behaviour change, socio-behavioural dimension, rural-urban divide, sharing economy) should not be on the agenda for 2025 due to lack of capacity. A fast-track on cities will be proposed.
- The participants expressed their individual interests in the course of the discussion:
  - Souran Chatterjee (HEB): has experience with scenario development and has HwL/DLS scenarios, but has no dedicated HwL, rather DLS and sufficiency. Proposes to build on the experiences of the India fast-track. Using EDITS findings and conceptual framework, any new scenario developed, should clearly put wellbeing in the center. HEB uses useful energy.
  - Masa Sugiyama (WG Protocol): Protocol has been under development, and we need to focus on strengthening what is most challenging. It is imperative that scenarios have a DLS/inequality aspect. Based on the experiences of the transport MCE, first efforts need to be placed on alighing baselines. Data have been collected, and floorspace data from different models differ, which already skews the baseline. All models should use one floorspace level. An effort to collect various floorspace data would be appreciated, because there exists no global source (such as EDGAE or IEA for energy)
  - Joyashree Roy (power sector model): the model projects electricity demand and intensity. It works with the peak and demand-shift. Efficiency scenarios use BAT, and include technological high end solutions. The model works for selected national levels.
  - Johan Velez (RECC): The model connects floorspace and material demand through thermal comfort. It runs for single countries in LAC and MENA. Extension is underway.
  - Yohei Yamaguchi and Shimoda, Yoshiyuki (TREES): Population and floorspace are drivers.
  - Kaveri Ashok (SAFARI model): their focus is on redistribution of floorspace to achieve 30m2/person across populations. It works with vintages and income classes.

        - Shan Hu (CBEEM (China)): There is no official floorspace statistics, therefore the first task is to fix a dataset. The model is hybrid, including climate zones and user types, combined with a physical model (buildings) and technology. The core scenario is already a sufficiency scenario. They find that floorspace satisfaction is at the level of 35 m2/person.
    - **In conclusion, WG Buildings should engage in MCE in 2025.**
        - First collect scenarios that already exist, some developed within EDITS.
        - Then tackle the challenges of baseline and historical data. For this collect (central database) and uniform floorspace data.
        - Projections should be at the level closest to humans and/or wellbeing. At the moment this is floorspace per capita (activity). There is a need for calibration (base year, target year).
        - The MCE for buildings needs to define the ultimate target of the scenarios (wellbeing, DLS, reduce inequality, etc.), then compare how models solve this problem.
        - A definition of indicators is needed. These should be closest to services/humans.
        - The group should have a common understanding of what the entry point is. We should not describe DLS (not IPCC compatible), but about wellbeing.

During the year, modelers from the WG and the WG co-leads had several meetings with WG Protocol to brainstorm and start to set-up the Model Complementarity Exercise for 2025. Other meetings were held with WG data to contribute to the data dashboard with buildings data, in particular floorspace and material demands.

WG ACTIVITIES IN 2024-25

The activities of the WG in the current fiscal year were multi-focused and aimed at linking across sectors and methods. The WG has been leaning on specific fast-track streams.

The WG published the first community review paper in November 2023, "Mastrucci, Niamir, Boza-Kiss, Bento, Wiedenhofer, Streeck, 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 paper gives account of how a range of bottom-up building sector modeling tools approach the representation of LED transformations. This paper was the starting point to sprout several fast-track projects, focusing on addressing specific gaps highlighted in the review work, such as including consideration of well-being in the developing countries (FT DLS-India), or assessing a broader range of co-benefits related to interventions in the buildings sector (FT Co-benefits).

- **Collaborating with other WGs:**

After focusing on mapping the buildings sector modeling practices and identifying research gaps, one direction to proceed is to collaborate with other WGs further. In particular to

- WG1 – Transport: collaborate on review paper on transportation modelling
- WG1 – Industry: collaborate on review paper on industry modelling
- WG2 – Data: data collection from buildings models in EDITS
- WG3 - Complementary Protocol: contribute with inputs on the data template and modelling protocol
- WG4 – Wellbeing: contribute to the conceptualization and assessment of health and wellbeing for the buildings sector

- **Interacting with running fast-track projects:**

The following fast-track projects were related to the Working Group in some ways.

Table 7. Mapping of fast-tracks according to their interaction with the working group 1 – buildings. Green = very strong collaboration and/or embeddedness; Orange = strong collaboration; Yellow = limited, but existing collaboration.

no.	Title	Collaboration details

FT23-1	High well-being with low energy demand: accounting for living standards in buildings modelling for the global south	The FT has been fully integrated into the WG. It was developed from WG work, enjoyed strong participation of the WG members, and the FT was co-lead by WG leads. Extension of the FT is hosted by the WG.
FT23-3	How much societal material stocks and resource use are needed for Decent Living Standards and high wellbeing?	Limited interaction, mostly through common participants and buildings sector comments.
FT23-4	New metrics to measure and value demand-side services and well-being	Medium level interaction. Several WG members participate in the FT, and collected buildings examples and data.
FT23-6	Crises as opportunities for accelerating the demand side energy transition	Limited interaction, based on providing examples for the fast-track.
FT23-7	Data gaps	High level of interaction. Though the FT is not embedded into the WG, a building sector group worked on the respective part of the FT. Data sharing was active.
FT24-1	WELL-with-LOW - Wellbeing Metrics and Assessment of LED-type Policy Options	Medium level interaction. Several WG members participate in the FT, and use data from the WG to enhance FT indicators on buildings.
FT24-2	Patterns of Diffusion in Social Innovations	Limited interaction. Buildings related datasets were used in the FT, but bilateral collaboration has been limited.
FT24-3	Method and Estimation of Cross-sectoral mitigation potential of Demand side solutions	Limited interaction. Buildings related datasets were used in the FT, but bilateral collaboration has been limited.
FT24-5	More benefits with lower demand-Quantifying the co-benefits of LED scenarios	The FT has been fully integrated into the WG. It was developed from WG work, enjoyed strong participation of the WG members, and the FT was co-lead by WG leads. Extension of the FT is hosted by the WG.

SUCCESSES AND CHALLENGES

The accomplished results were achieved thanks to the excellent contributions and engagement of EDITS members in different activities. Coordination within the WG and with other WGs, FT project leads, and EDITS leadership was essential for supporting EDITS collaborations and activities and achieve impactful results.

The review paper was a considerable effort from almost all group members, including authors, but also other members who supported the process. A similarly large scale effort would have been ambitious, therefore the WG has been used a platform for discussions and to generate small-team activities, among them the fast-tracks.

Though it has been challenging to keep coherence as a WG without a large common effort, after the main WG meeting on 7 November, it has been decided to engage in the MCE. It is foreseen that this exercise will be very impactful, though difficult.

WG activities planned in 2025-26:

For 2025-26 we are planning to run a model comparison exercise (MCE) for the buildings sector as a follow-up to the work done in the transport sector. The results from FTs related to buildings and previous WG activities (e.g. review paper) will be used to establish the modelling and scenario protocol. For this activity, we would need support from other EDITS members and cross-WG collaboration to successfully engage with the modelling team, establish a modelling protocol, collect modelling data, and analyse the results. In addition, we will continue supporting EDITS

activities across WGs, as well as FT works, and dissemination. In particular, we have already discussed the new FT proposals related to this WG and discussed potential collaborations and contributions.

Table 8. List of WG1 – Buildings members as of January 2025

Name	Main affiliation	Country
Keigo Akimoto	Research Institute of Innovative Technology	Japan
Karthik Akkiraju	Yale University	USA
Mohit Arora	King's College London	UK
Kaveri Ashok	Center for Study of Science, Technology and Policy	India
Ronita Bardhan	University of Cambridge	UK
Nuno Bento	University Institute of Lisbon	Portugal
Vered Blass	Tel Aviv University	Israel
Yekatherina Bobrova	University of Oxford	UK
Talita Borges Cruz	Universidade Federal do Rio de Janeiro	Brazil
Adel Boumerzoug	Central European University	Austria
Benigna Boza-Kiss	International Institute for Applied Systems Analysis	Austria
Mariaester Cassinelli	RFF-CMCC European Institute on Economics and the Environment	Italy
Souran Chatterjee	University of Plymouth School of Geography, Earth and Environmental Sciences	UK
Aditya Chunekar	Prayas	India
Enrico Cofler	Polytechnic of Milan	Italy
Luisa Cordroch	Europa-Universität Flensburg	Germany
Felix Creutzig	Mercator Research Institute on Global Commons And Climate Change	Germany
Vassilis Daioglou	PBL Netherlands Environmental Assessment Agency	Netherlands
Nandini Das	Climate Analytics	India
Ramit Debnath	University of Cambridge	UK
Ninaad Desai	Asian Institute of Technology	Thailand
Srihari Dukkipati	Prayas	India
Oreane Edelenbosch	International Research University - Universiteit Utrecht	Netherlands
Wei Feng	Chinese Academy of Sciences, Shenzhen Institute of Advanced Technology	China
Jill Ferguson	Stanford University	USA
Vivien Fisch-Romito	University of Lausanne	Switzerland
Tomer Fishman	Leiden University	Netherlands
Albane Gaspard	Agence de la Transition Ecologique	France
Ankita Gaur	University College Cork	Ireland
James Glynn	ESMA	Ireland
Arnulf Grubler	International Institute for Applied Systems Analysis	Austria
Jennifer Hawkin	University of Cambridge	UK
Marie Josefine Hintz	Technical University Berlin	Germany
Tianzhen Hong	Lawrence Berkeley National Laboratory	USA
Shan Hu	Tsinghua University	China
Ana Jacomit	Universidade Federal do Rio de Janeiro	Brazil
Joni Jupesta	United Nations University Institute for Advanced Studies of Sustainability	Japan
Dahyun Kang	Research Institute of Innovative Technology	Japan
Paul Kishimoto	International Institute for Applied Systems Analysis	Austria
Veronika Kiss	GreenFormation	Hungary
Ravishankar Krithika	Center for Study of Science, Technology and Policy	India
Poornima Kumar	University of Oxford	UK
Chandrakiran Lakshmisha	Center for Study of Science, Technology and Policy	India
Giacomo Marangoni	RFF-CMCC European Institute on Economics and the Environment	Italy
Francois Marechal	Swiss Federal Institute of Technology Lausanne	Switzerland
Yves Marignac	négaWatt Association	France
Luis Martinez	International Transport Forum	France
Alessio Mastrucci	International Institute for Applied Systems Analysis	Austria
Vincent Minier	Schneider Electric Sustainability Research Institute	Sweden
Firuz Ahamed Nahid	Asian Institute of Technology	Thailand
Yuko Nakano	Research Institute of Innovative Technology	Japan
Leila Niamir	International Institute for Applied Systems Analysis	Austria
Yuki Numata	Rocky Mountain Institute	USA
Felicitas Ortlieb	University of Stuttgart	Germany

Shonali Pachauri	International Institute for Applied Systems Analysis	Austria
Stefan Pauliuk	University of Freiburg	Germany
Setu Pelz	International Institute for Applied Systems Analysis	Austria
Merle Quade	International Institute for Applied Systems Analysis	Austria
Keywan Riahi	International Institute for Applied Systems Analysis	Austria
Roberto Schaeffer	Universidade Federal do Rio de Janeiro	Brazil
Yoshiyuki Shimoda	Osaka University; Urban Energy System Lab. / Research Institute of Innovative Technology for the Earth (RITE)	Japan
Bianka Shoai-Tehrani	Réseau de Transport d'Electricité	France
Keita Shono	Osaka University	Japan
Shreya Some		Denmark
Jan Streeck	Universität für Bodenkultur, Institut für Soziale Ökologie	Austria
Masahiro Sugiyama	University of Tokyo	Japan
Aparna Sundaresan	Center for Study of Science, Technology and Policy	India
Deepthi Swamy	International Institute for Applied Systems Analysis	Austria
Massimo Tavoni	Politecnico di Milano	Italy
Johannes Thema	Wuppertal Institute for Climate, Environment and Energy, Energy Policy Research Unit	Germany
Gwenny Thomassen	Ghent University (50%); University of Antwerp (50%)	Belgium
Dimitri Tientega	Global Network of Fifty Youth Committed to the Climate / Jeunes Acteurs de l'Energie	Burkina Faso
Diana Urge-Vorsatz	Central European University	Austria
Parth Vaishnav	University of Michigan	USA
Bas van Ruijven	International Institute for Applied Systems Analysis	Austria
Johan Vélez Henao	University of Freiburg	Germany
Doris Virág	University of Natural Resources and Life Sciences, Institute of Soial Ecology	Austria
Pat Wagner	International Institute for Applied Systems Analysis	Austria
Dominik Wiedenhofer	Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna (BOKU)	Austria
Charlie Wilson	University of Oxford	UK
Yohei Yamaguchi	Osaka University	Japan
Nan Zhou	Lawrence Berkeley National Laboratory (LBNL) - Building Technology and Urban Systems Division / Net Zero World Action Center (NZW), Technical Program Manager	USA

PART 5. OUTREACH

EDITS has a broad range of public channels, ranging from traditional websites to social media. EDIYS often engages with the public and policy makers, and always organizes a session at the Conference of the Parties of the UNFCC.

ONLINE PRESENCE

Previous social media channels have been kept, but posts have been reduced on X and Facebook, while focused more on Linkedin and Bluesky in line with general academic trends:

- central webpage: https://iiasa.ac.at/projects/edits (Figure 12)
- @edits-community.bsky.social
- https://twitter.com/EDITS_Community
- https://www.linkedin.com/groups/14104139/
- https://www.facebook.com/profile.php?id=100083345312269
- https://www.youtube.com/@editsnetwork9803

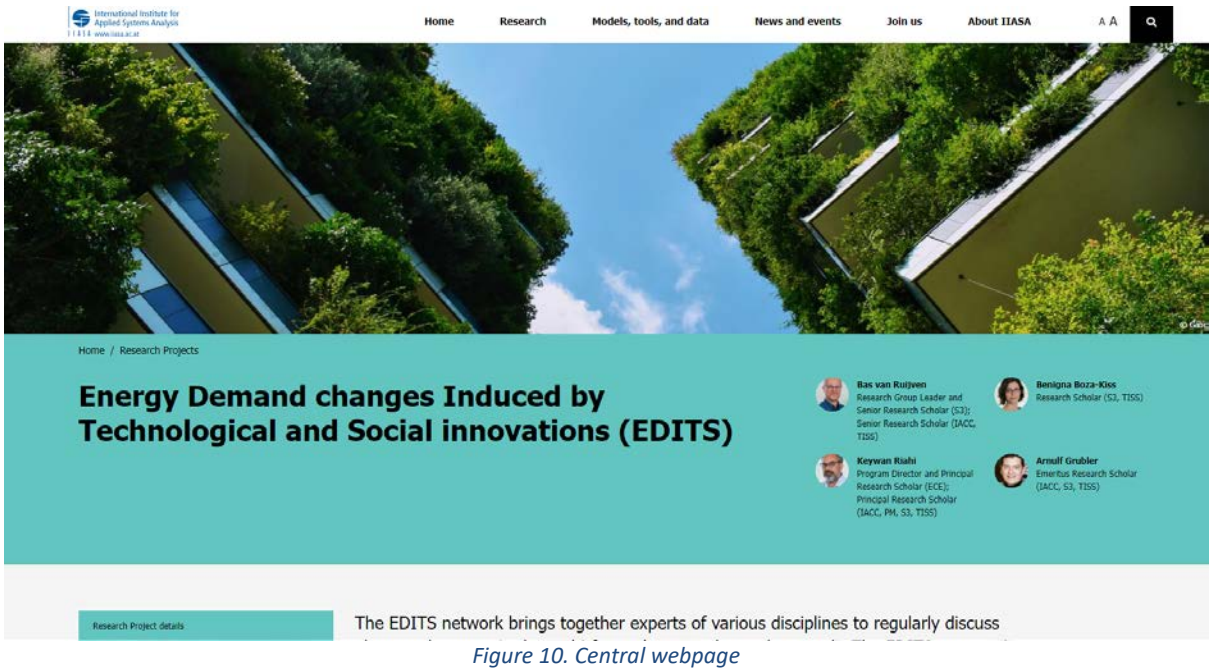


Figure 10. Central webpage

PLAN: *The website should be extended in 2025-26, potentially extending with numerous subpages. The main focus of the extension will be to promote research output more, and summarize published material and reports.*

We also plan to provide a broader opportunity for authors of papers under EDITS to send us short summaries that can be promoted on the social media platforms.

POLICY AND PUBLIC ENGAGEMENT

Webinars

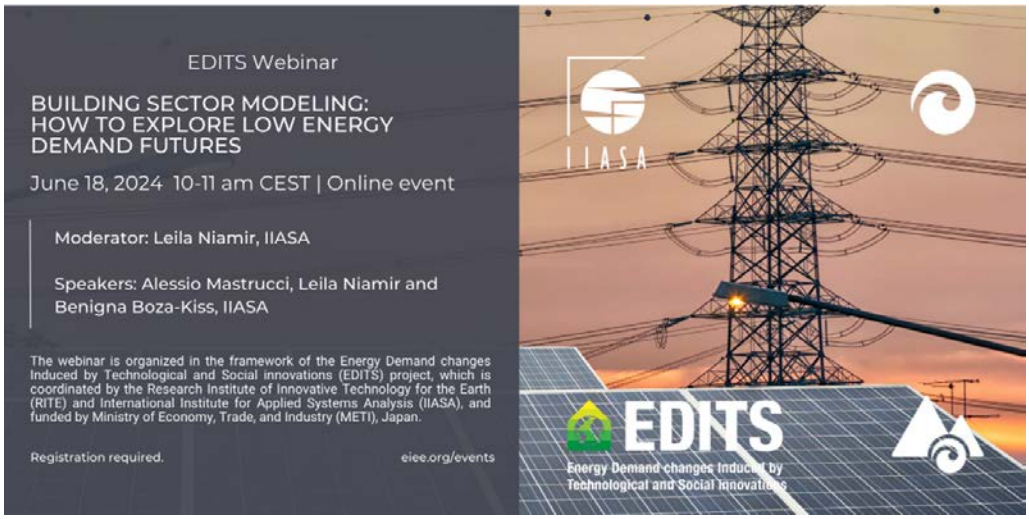
The Community continued to disseminate results through the established series of webinars, coordinated by IIASA and European Institute on Economics and the Environment (CMCC-EIEE). The EDITS webinars are accessible through a unique playlist managed by the EDITS Youtube channel at: https://youtube.com/playlist?list=PLurAibr12t75IEaapTEqYSa-IPTziLRgF&si=H3kS_QZnEyHGTpNo. In 2024-25 **four EDITS webinars** were held:

- **Webinar #6:** Nuno Bento, Integrated Researcher at the DINÂMIA'CET research center at University Institute of Lisbon – Iscte | Leverage demand-side policies for energy security | Recording is available at https://www.youtube.com/watch?v=Hd3MRA6qsI4

  Time: 06.06.2024 | 11:00 (CEST)

- **Webinar #7:** Alessio Mastrucci, IIASA and Benigna Boza-Kiss, IIASA | Building sector modeling: how to explore low energy demand futures | Recording is available at https://www.youtube.com/watch?v=vP0Io_8Oplk

  Time: 18.06.2024 | 10:00 (CEST)



- **Webinar #8**: Paul Brockway, Faculty of Environment, University of Leeds, UK; Carey King, - Energy Institute, The University of Texas at Austin; Jaime Nieto Vega, University of Valladolid, Spain and the University of Leeds, UK | New avenues for macro-economic modelling under global constraints: The HARMONEY, MARCO, and MEDEAS models | Recording is available at https://youtu.be/FdtfXWbi5E0

  Time: 16.07.2024 | 16:00-17:30 CEST // 9-10:30 a.m. CDT

- **Webinar #9:** Oreane Edelenbosch and Detlef van Vuuren, University of Utrecht; Peter Berrill, Leiden University; Edgar Hertwich, Norwegian University of Science and Technology | Circular Economy Modelling for Climate Change Mitigation – Updates from the Horizon Europe CIRCOMOD project | Recording is available at https://www.youtube.com/watch?v=EC-iZd3tVDc
  Time: 10.02.2025 | 9:15-10:30 CET

PLAN: *For the next year, we plan to arrange 2-4 online webinars, mainly presenting the results of fast-track projects, and modeling exercises that will make IPCC-ready research results more accessible.*

COP29 side-event

EDITS organized a COP29 Side-event at Japan Pavilion, United Nations Climate Change Conference in Baku, Azerbaijan on 15 November, 2024 at 15:45 -17:00 (local time), and online via zoom streaming.

The program of the event is below.

Moderator: Joyashree Roy, Asian Institute of Technology, Thailand
15:45-15:50 Welcome and GX policies in Japan - Hiroshi Maeda, Director, Global Environmental Affairs Office, GX Policy Group, Ministry of Economy, Trade and Industry (METI), Japan

15:50-15:55 Opening remarks on social and technological transformation with low demand - Bas van Ruijven, International Institute for Applied Systems Analysis (IIASA), Austria

15:55-16:05 Importance of demand-side solutions for the net-zero society transformation - Keigo Akimoto, Research Institute of Innovative Technology for the Earth (RITE), Japan

16:05-16:15 Innovation for socio-technological-economic transformation - Greg Nemet, University of Wisconsin-Madison, La Follette School of Public Affairs, Wisconsin Energy Institute, USA

16:15-16:25 Urban space and society: the role of demand-side innovations - Diana Ürge-Vorsatz, Professor, Central European University (CEU), Austria / Vice-Chair, IPCC

16:25-16:35 Policy as a catalyst in the green transition for developing countries - Joyashree Roy, Professor, Asian Institute of Technology (AIT), Thailand

16:35-17:00 Panel comments: innovation and mitigation – Joyashree Roy, Asian Institute of Technology, Thailand

The event started with a welcome by Mr. Hiroshi Maeda from METI and a kick-off and welcome speech by Dr. Keigo Akimoto, RITE. Dr. Bas van Ruijven argued how demand-side solutions deliver system-wide changes and leverage up-stream savings through the energy cascade (Figure 1). Social and technological transformations are equally important in enabling low energy demand futures.

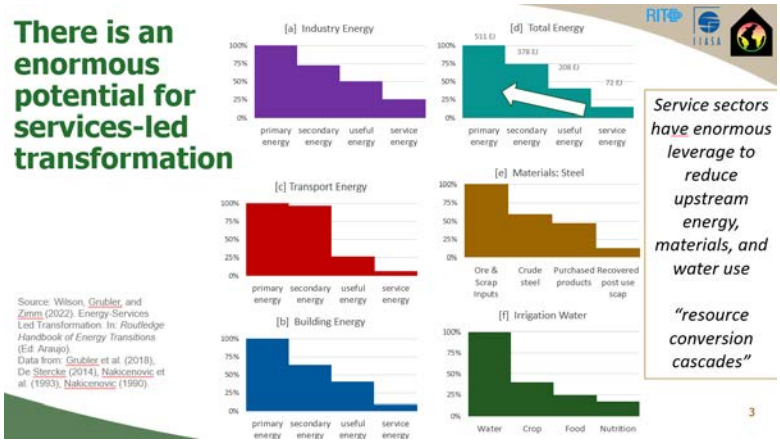


Figure 1. The energy cascade. Source: Wilson et al. 2022. in the presentation by Bas van Ruijven.

Social innovations follow similar patterns as technological innovations distribution. Early adopters are critical, because they enable the testing of social change. These individuals are typically more risk-taking, environmentally savvier, and often have social concerns. Mainstream adopters avoid risk, nevertheless they willingly follow through and adopt proven social practices, either because of the benefits or policy backing. Dr Nemet said that his research shows that the formative phase of social innovation patterns is critical, it can serve as a turning point, as well as define the speed of the spread. Social innovations could still enable fast decarbonization, which is the hope to still achieve climate goals. Dr Roy's policy example on mobility fuel-mix transformation in Pakistan demonstrated the emphasis on relevant and effective policies at turning points of the pattern formation, but especially in the roll-out phase mentioned. The policy sequence for fuel shift was very fast compared to other countries building on the local fuels, interest and collaboration, as well as policy. The Sufficiency Economy Principle in Thailand is an astounding policy example in the developing world that lays the intersection of energy savings and efficiency. It has been a cornerstone of the Thai policy system since 1973, way before the international support (e.g. IPCC 2022, GEA 2012, UNDP 2007). From 2007 SEP is integrated into Thai constitution.

Participants raised the issue of financing, especially in comparison to other finance needs, such as renewables, SDGs, carbon removal, etc. Dr. Urge-Vorsatz had previously shown that the costs of standard construction and advanced construction are in the same range (Figure 2). The panel agreed that financing is a key issue, and while energy-demand solutions are known to be very cheap relative to other interventions, there seem to be a combination of barriers that together limit full-fledged upscaling.

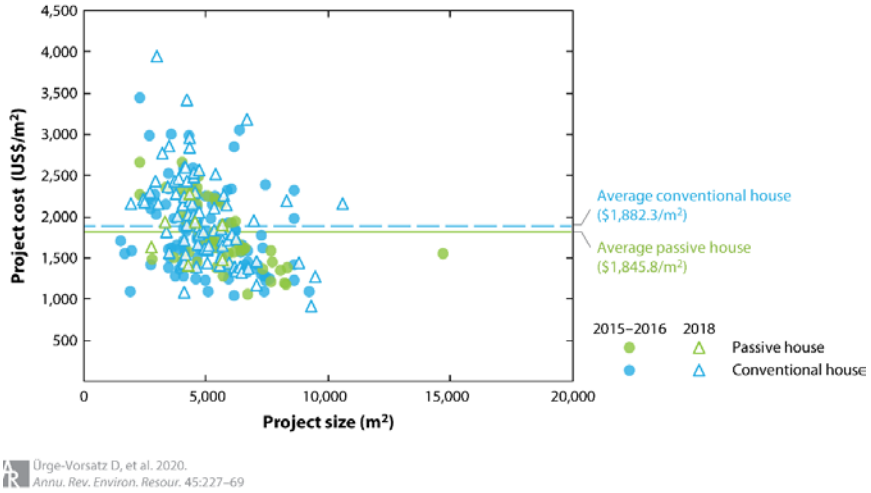


Figure 2. Project costs of standard and advanced constructions. Source: Urge-Vorsatz et al. 2020 in Presentation by Diana Urge-Vorsatz.

Dr van Ruijven pointed out that the benefits that other than financial and climate, can be really emphasized (social, wellbeing, environmental, etc) impacts. According to Dr Urge-Vorsatz, financing of various targets could be cross-used, e.g. demand-side measures bring many other social benefits, water quality and quality improvements, have SDG relevance, thus climate finance and SDG finance largely overlap. We can achieve more targets with single investments, at the end of the day.

Finally, a very interesting proposal was raised by a colleague from the Danish government. Other climate areas, such as renewables, fossil fuels, etc. have clearcut pledges, and it would be interesting what kind of energy-demand targets or pledges would make sense. Dr. Nemet pointed out that there are many and successful energy saving yearly or overall targets in many US states, and in the EU and also other countries. These are generally successful and effective. Dr Roy reminded that the IPCC identified 40-70% mitigation effort could be covered by demand-side solutions. Dr Urge-Vorsatz emphasized the leveraging effects of more efficient and sufficient housing, with impacts on materials, and urban environments, leading to reduced impacts multiplying, while leveraging multiple benefits.

Dr van Ruijven informed the participants that there is a Transport Pledge at the COP29, which is in fact mostly built on demand-side measures, and encourages all to sign. Dr Keigo Akimoto indicated that the research and expert community working together within the EDITS network, Energy Demand changes Induced by Technological and Social innovations furthers the knowledge and evidence base in these discussed areas and welcomes further discussion on energy-demand measures and solutions.

Information about the event can be found at: https://iiasa.ac.at/events/nov-2024/pathway-to-green-transformation-of-society-edits-at-cop29

PLAN: In the next financial year, EDITS plans to attend the next COP30 in Brazil with higher number of participants.

ANNEX 1: EDITS ANNUAL CONFERENCE SUMMARY

2024 Annual EDITS Conference on High with Low scenarios towards AR7

8-10 October 2024 with side-events on 7 October and 11 October

Laxenburg, Austria

Summary of the conference and key take-aways

There is a double sided issue that EDITS has intended to focus on, simply described as the consumption corridor. At start, we have focused on mitigation of climate change. We have used climate models and energy system models to describe a future where significantly lower energy demand can protect the climate integrity. In this framework, we have used wellbeing as a co-benefit, among others, that are the sweet spots of the policy decisions. However, as we progressed, we have placed more and more emphasis on human needs and how wellbeing could be considered the focal point of our analysis and climate mitigation becomes the co-benefit.
Significant differences exist in the national climate mitigation measures and costs, while different nations conceive their burden to share in the light of fairness. In response to the need for understanding the gap between action and targets, as well as to better define what is necessary to close the gap, the first Global Stocktake (GST) was adopted at the 28th UNFCCC Conference of the Parties (COP28) in November 2023. It is agreed that country actions need to step up their effective actions without delay, including fossil fuel phase out, while ensuring equity and fairness, and leveraging all energy and decarbonization technologies and other changes, such as social innovations and structural changes towards the common goal of net zero. It is crucial to consider the various circumstances in each country and sector to achieve genuinely effective measures.
On the contrary, wellbeing is more universal. People around the globe should have access to the same levels of provisioning, and an increased equality in satisfying the needs of all is expected to lead to a more just system to tackle climate change and other environmental boundaries. To this end scenarios and theroretical research in EDITS should align with the concept of consumption corridors, making sure that everyone has access to decent living standards and a good life, while limiting overconsumption beyond what is necessary (i.e. sufficient).

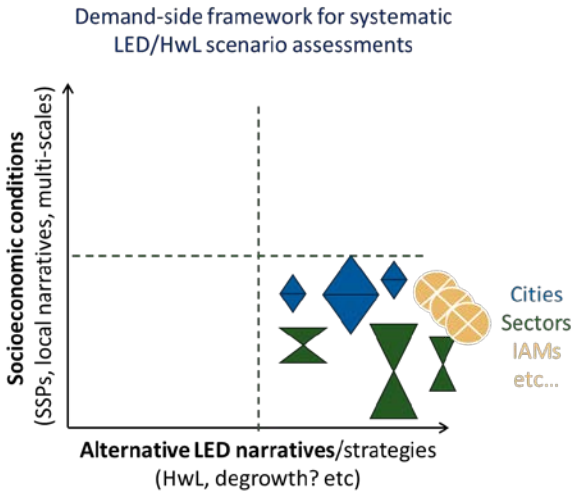
Within this framework, transformation of how societies operate, while providing the same or improved services has been shown to have incremental value. It is the actions and solutions on the demand-side that can engrave improvements for the people while also leveraging system-wide transformations towards sustainability. Improving wellbeing, reducing inequality, increasing security are the center of the value systems and thus should be the ultimate goal of decisions. Due to the multiplicative effect on the supply-side and infrastructure, demand-side transformation provide significant climate mitigation and adaptation benefits, too. It has been shown, but needs to reinstated that demand-side measures are often implemented easier, faster and at lower costs, as opposed to common belief, especially compared to supply side measures.

These characteristics and a broader understanding substantiate more research and further evidence, as well as improved communication. There is a need to strengthen the assessment of the energy-demand side, based on the invitation in the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC). The Energy Demand changes Induced by Technological and Social innovations (EDITS) initiative embarked to deepen the understanding of demand-driven energy systems, energy and material demand projections based on technological-social-infrastructural interactions at global and granular levels, and their nexus with wellbeing and the SDGs. EDITS pursues collaborative research to identify gaps and potentials to enhance modeling, empirical analysis, and communication about demand-side solutions and an energy system transformation.

Three priority themes have been identified with the Community by the end of the Annual Meeting. These are expected to underpin any activity and research direction within the Working Groups, Fast-tracks, and Team works: (in parenthesis: the space in the EDITS set-up, where the priority could be tackled)

Priority 1. Progressing modeling

- Improve the framework for systematic exploration of the (demand) solution space (fast-track)
- Connect sectoral models (SM) and IAM models. (WG + members)
- Improve scenario data collection, translation, develop Scenario Compass (WG + members)



Priority 2. Strengthening policy relevance

- Assess performance of demand-side policies beyond climate: wellbeing, inequality, justice, jobs (fast-track/members)
- Research policies that hamper demand-side solutions (fast-track/members)
- Develop and apply a methodology for demand policy evaluation (fast-track/members), focusing on:
    - ambition level, benchmarking, justice
    - governments and businesses
- Carry out acceptability and feasibility assessment, considering these are asymmetric and dynamic (WG/ fast-track/members)

Priority 3. Wellbeing reframing

- Develop a more comprehensive wellbeing metric and evaluate scenarios with that (fast-track)
- Include quality of service provisions and inequality/access though developing methodology and collecting data (WG/ fast-track/members)
- Adapt the consumption corridor, floor and ceiling. Focus on demand-side relevant defintion, quantification and conceptualization (WG)

Actionable items for EDITS

In 2024, EDITS must push ahead with on-going long-term tasks, such as the model complementary exercise. In this, we develop and collect scenarios that drastically reduce energy demand, and assess the impacts on climate, economy and wellbeing, among others. In parallel, EDITS also advances with selected key topics in a speedy manner as fast-track streams. It is time to increase engagement with other researchers, policy-makers and implementers.

The conclusions of the Annual Meeting imply the following actions for 2025 for EDITS:

- The Working Groups should serve as discussion platforms, organize specific meetings a few times during the period. They should be the brewing pots for new ideas and activities
- The Model Complementarity Exercise (MCE) should continue. The progress is very challenging because it is a long process. The transport MCE should achieve a collection of scenarios and a common publication. The group of models should remain limited (3), but open the floor for potential interested others.

- MCE for Buildings should be started in 2025 with an aim to complete it by the end of 2027. As opposed to MCE Transport, it should aim to include many models and collect existing and/or develop complete scenarios that comply with agreed indicators of HwL.
- Fast-tracks should be invited, and they should respect the above priorities.
- Invited fast-tracks could completement the important gaps in terms of priorities.
- EDITS should still target 15 papers per year, which are highly relevant for IPCC AR7 and the Cities report.
- Outreach should be strengthened.

ANNEX 2: EDITS ANNUAL CONFERENCE LIST OF PARTICIPANTS

The group:

Ernest Aigner Leuphana University Lüneburg (SESI), Vienna University of Economics and Business	Keigo Akimoto Research Institute of Innovative Technology (RITE)	Marlin Arnz Institute of Climate and Energy Systems (ICE-2, TU Berlin; WIB), Reiner Lemoine Institute, Berlin
Kaveri Ashok Center for Study of Science, Technology and Policy (CSTEP)	Andre Baumgart Universität für Bodenkultur, Institut für Soziale Ökologie (BOKU/SEC)	Nuno Bento University Institute of Lisbon (DINÂMIA'CET-Iscte-IUL)
Benigna Boza-Kiss International Institute for Applied Systems Analysis (IIASA)	Elina Brutschin International Institute for Applied Systems Analysis (IIASA)	Tao Cao University of Tokyo, Institute for Future Initiatives (Univ. Tokyo)
Souran Chatterjee University of Plymouth School of Geography, Earth and Environmental Sciences (UOP)	Joyee Chatterjee Asian Institute of Technology (AIT)	Yi-chun Chen The Institute of Energy Economics, Japan (IEEJ)
Enrico Cofler RFF-CMCC European Institute on Economics and the Environment (RFF-CMCC EIEE)	Felix Creutzig [online] Mercator Research Institute on Global Commons And Climate Change (MCC)	Simon De Stercke International Institute for Applied Systems Analysis (IIASA)
Ninaad Desai Asian Institute of Technology (AIT)	Oreane Edelenbosch International Research University - Universiteit Utrecht (UU),	Vivien Fisch-Romito University of Lausanne (UNIL)
Tomer Fishman Leiden University (CML)	Maximilian Forberg Chalmers University of Technology	Atsuko Fushimi Research Institute of Innovative Technology (RITE)
Lydia Gericke International Institute for Applied Systems Analysis (IIASA)	James Glynn [online] European Securities and Markets Authority (ESMA)	María Fernanda Godoy León Leuphana University Lüneburg (SESI)
Arnulf Grubler International Institute for Applied Systems Analysis (IIASA)	Kreinin Halliki Forschungsinstitut für Nachhaltigkeit - Helmholtz-Zentrum Potsdam (RIFS Potsdam)	Takuya Hara International Institute for Applied Systems Analysis / Toyota Motor Company (IIASA / TMC)
Jennifer Hawkin University of Cambridge	Ayami Hayashi Research Institute of Innovative Technology (RITE)	Shan Hu Tsinghua University (BERC)

Hiroyoshi Iwata University of Tokyo (IFI)	Aneeque Javaid International Institute for Applied Systems Analysis (IIASA)	Yiyi Ju International Institute for Applied Systems Analysis (IIASA)
Tae Yong Jung Yonsei University (YONSEI)	Joni Jupesta United Nations University Institute for Advanced Studies of Sustainability (UNU-IAS)	Jarmo Kikstra International Institute for Applied Systems Analysis (IIASA)
Siir Kilkis The Scientific and Technological Research Council of Türkiye and IPCC (IPCC / TÜBİTAK)	Yong-Gun Kim Yonsei University (YONSEI)	Norihiro Kimura Ministry of Economy, Trade, and Industry (METI)
Paul Kishimoto International Institute for Applied Systems Analysis (IIASA)	Lukas Kranzl TU Wien	Volker Krey International Institute for Applied Systems Analysis (IIASA)
Poornima Kumar University of Oxford (ECI)	Florian Maczek International Institute for Applied Systems Analysis (IIASA)	Luis Martinez International Transport Forum (ITF/OECD)
Eric Masanet University of California, Santa Barbara (UCSB)	Alessio Mastrucci International Institute for Applied Systems Analysis (IIASA)	David McCollum Oak Ridge National Laboratory / International Institute for Applied Systems Analysis (ORNL / IIASA)
Joel Millward-Hopkins University of Leeds (Univ. Leeds)	Jihoon Min International Institute for Applied Systems Analysis (IIASA)	Jongwoo Moon Yonsei University
Johannes Morfeldt Chalmers University of Technology	Miyuki Nagashima Research Institute of Innovative Technology (RITE)	Takahiro Nagata Research Institute of Innovative Technology (RITE)
Firuz Ahamed Nahid Asian Institute of Technology (AIT)	Yuko Nakano Research Institute of Innovative Technology (RITE)	Gregory Nemet Wisconsin Energy Institute (WEI
Leila Niamir International Institute for Applied Systems Analysis (IIASA)	Sascha Nick EPFL Laboratory of Environmental and Urban Economics (EPFL)	Yuki Numata Rocky Mountain Institute (RMI)

Xunmin Ou Tsinghua University	Shonali Pachauri International Institute for Applied Systems Analysis (IIASA)	Stefan Pauliuk University of Freiburg (Univ. Freiburg)
John Pelayo Pritchard International Transport Forum (ITF/OECD)	Keywan Riahi International Institute for Applied Systems Analysis (IIASA)	Joyashree Roy Asian Institute of Technology (AIT), Jadavpur University (JU), and Global Change Programme (GCP-JU)
Fuminori Sano [online] Research Institute of Innovative Technology (RITE)	Roberto Schaeffer Universidade Federal do Rio de Janeiro (UFRJ/COPPE)	Karl Scheifinger International Institute for Applied Systems Analysis (IIASA)
Yoshiyuki Shimoda Osaka University; Research Institute of Innovative Technology for the Earth (RITE)	Bianka Shoai-Tehrani Réseau de Transport d'Electricité (RTE)	Jubair Sieed Research Institute of Innovative Technology (RITE)
Zakia Soomauroo Reiner Lemoine Institut (RLI), TU Berlin, Sustainable Economics of Human Settlements	Ashok Sreenivas Prayas (PEG)	Linda Steg University of Groningen (Univ. Groningen)
Jan Streeck Universität für Bodenkultur, Institut für Soziale Ökologie (BOKU/SEC)	Masahiro Sugiyama University of Tokyo, Institute for Future Initiatives (UTokyo IFI)	Massimo Tavoni [online] Politecnico di Milano School of Managmenet (POLIMI)
Gwenny Thomassen Ghent University; University of Antwerp	Sirayuth Thongprasert Asian Institute of Technology (AIT)	Gamze Ünlü International Institute for Applied Systems Analysis (IIASA)
Diana Urge-Vorsatz Central European University (CEU), IPCC	Bas van Ruijven International Institute for Applied Systems Analysis (IIASA)	Anne van Valkengoed University of Groningen (RUG)
Johan Vélez Henao University of Freiburg (Univ. Freiburg),	Elena Verdolini RFF-CMCC European Institute on Economics and the Environment (RFF-CMCC EIEE)	Pat Wagner International Institute for Applied Systems Analysis (IIASA)
Dominik Wiedenhofer Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna (BOKU) (BOKU/SEC)	Frauke Wiese [online] Europa-Universität Flensburg (EUF-EnSu)	Charlie Wilson University of Oxford (ECI), International Institute for Applied Systems Analysis

Yohei Yamaguchi Osaka University		Carina Zell-Ziegler [online] Oeko-Institut		Jingjing Zhang Lawrence Berkeley National Laboratory (LBNL)
Nan Zhou Lawrence Berkeley National Laboratory (LBNL); Net Zero World Action Center (NZW)		Caroline Zimm International Institute for Applied Systems Analysis (IIASA)		

ANNEX 3: EDITS ANNUAL AGENDA AND PROGRAM

Program [all times in CEST]

SIDE-EVENT DAY: 7 October, Monday

09:00 Public transport pool to IIASA (see Logistic Note, look for colleagues to travel together)

10:00-12:00 FT24-3 CrossSector (open) Gvishiani room

10:00-11:30 FT24-2 Social Innovations (closed) Wodak room

11:30-13:00 Lunch break (own costs)

13:00-14:30 WG Building meeting (open) Gvishiani room

Organizers: Alessio Mastrucci, IIASA (Austria) and Leila Niamir, IIASA (Austria)

Session content: we will explore interests of this community in running a model complementarity exercise (MCE) around buildings and appliances within EDITS, to be rolled out in 2025. Other topics of discussion are of course very welcome (please, let us know!)

13:00-14:30 FT24-2 Social Innovations (closed) Wodak room

13:30 Public transport pool to IIASA (see Logistic Note, look for colleagues to travel together)

14:00 14:30 Coffee

14:30-17:30 EDITS strategy meeting (closed meeting for invited members, WG leads) **Wodak room**

17:45 Shuttle bus from Laxenburg to Vienna (Motel One)

CORE DAY: 8 October, Tuesday

08:00 **Shuttle bus** pick-up from Vienna (see Logistic Note for map)

08:30-09:00 Arrival and registration / welcome coffee

09:00-10:45 Session 1. Opening and the way forward [Plenary session] Gvishiani room

We start a discussion on how to situate ourselves within the wider research and policy community. This topic will come back in latter sessions. We start with a keynote speech to overview the IPCC process and the need for demand-side perspective in it, followed by an open discussion on the role and outputs of EDITS and demand-side research in the green transformation and how this should be reflected in the next IPCC cycle.

Moderator**: Bas van Ruijven,** IIASA (Austria), Rapporteur: Simon De Stercke

09:00-09:05 Welcome and goals of the meeting
Bas van Ruijven, IIASA (Austria)

09:05-09:20 EDITS achievements in a nutshell
Bas van Ruijven and **Benigna Boza-Kiss**, IIASA (Austria)

09:20-09:35 Welcome and future plans of EDITS
Keigo Akimoto, RITE (Japan)

09:35-09:45 Japan's GX Strategies and the role of the demand-side
Norihiro Kimura, METI (Japan)

09:45-10:00 Demand-side evidence-base in IPCC AR6 and AR7

Siir Kilkis, Vice-Chair, IPCC WG III, Scientific and Technological Research Council (Türkiye)

10:00-10:45 EDITS scoping and strategy in the light of IPCC AR7 – moderated plenary discussion

10:45-11:10 Coffee break

11:10-12:00 Session 2. Demand-side data [Plenary session] Gvishiani room

The Working Group data will give a glimpse of the varied activities within the WG and beyond.
Organizers: Oreane Edelenbosch, Nan Zhou, Joyashree Roy, Leila Niamir, Jingjing Zhang

- Showcasing WG Data core products (meta-database, indicator dashboard, cost and benefit data collection, data gaps identification, etc.)
- Discussion on progressing and using the products already available and next steps

12:00-14:00 Lunch break Schlossrestaurant

14:00-15:30 Session 3. Break-out Groups on wellbeing and sufficiency

The Break-out-Groups (BOGs) feature a few kick-off presentations around the topic, followed by group discussion on how these relate to each other and other research and activities within EDITS.

BOG 3.1: Putting wellbeing in the center Gvishiani room

Moderator: **Sascha Nick,** EPFL (Switzerland), Rapporteur: Jennifer Hawkin, University of Cambridge (UK)

Presentations (3-5 mins) followed by discussion:

- Can perceived impacts on quality of life help us to better understand people's climate policy preferences? Empirical results from the Netherlands

Anne van Valkengoed, University of Groningen (the Netherlands)

- Low-Demand with high well-being in Global south: more than energy savings with LED

Souran Chatterjee, University of Plymouth (the UK)

- Wellbeing and justice in scenarios

Elina Brutschin, IIASA (Austria)

Discussions about (a) links between perceptions of policy impacts, stated preferred inequalities, and fairness / justice, (b) energy use per relevant segment and gaps, and impact on wellbeing, (c) how to effectively engage stakeholders on DLS, wellbeing, justice, and country / sub-country climate commitments.

BOG 3.2: Sufficiency in the world regions Wodak room

Moderator: **Jingjing Zhang**, LBNL (USA), Rapporteur: Sirayuth Thongprasert, AIT (Thailand)

Presentations (10 mins) followed by discussion

- Sufficiency Principle in practice South-east Asian Region

Joyashree Roy, AIT (Thailand)

- New modelling framework to represent broader demand-side evolutions – sufficiency as well as other possibilities

Bianka Shoai-Tehrani, RTE (France)

- Fair enough: short term sufficiency strategies against daily energy use inequalities among the Swiss population

Vivien Fisch-Romito, University of Lausanne (Switzerland)

- Building energy sufficiency, and sufficiency measures with well-being and equality in China's building sector

Hu Shan, Tsinghua University (China)

Discussions about sufficiency approaches in the Global North and Global South.

15:30-16:00 Coffee break

16:00-17:00 Session 4. Discussion Break-out Groups

These Break-out-Groups (BOGs) focus specific areas of the demand-side and allow for group discussions.

BOG 4.1: Demand across sectors: materials **Gvishiani room**

Moderator: **Miyuki Nagashima**, RITE (Japan), Rapporteur: Yiyi Ju, IIASA (Austria)

Presentations (5-10 mins) followed by discussion:

- Circular economy modelling for Climate Change Mitigation in the CircoMod project

Oreane Edelenbosch, Universiteit Utrecht (the Netherlands)

- The contribution of circular economy strategies towards achieving net-zero GHG emissions: Activities in the CircEUlar project

Volker Krey, IIASA (Austria)

- Implications of low demand scenarios in the global bulding stock - materials and energy

Stefan Pauliuk, University of Freiburg (Germany)

BOG 4.2: Communicating the story of demand **Wodak room**

Moderator: **Benigna Boza-Kiss**, IIASA (Austria), Rapporteur: Poornima Kumar, University of Oxford (UK)

Session content: Group discussion about how to position and present the demand-side to wider audience. We have already invited some input previously, and many EDITS authors have published that touch on this. However, a wider consensus from the EDITS network is targeted. We want to have ideas on what we consider as core elements of LED/HwL futures, what these mean in different regions or are they universal. Ideally, we want to collect 10 (or 5 or 7) key messages that must be heard beyond EDITS.

Introduction by **Benigna Boza-Kiss**, IIASA (Austria) and intervention by **Joyee Chatterjee**, AIT (Thailand) are followed by structured discussion in workshop style.

BOG 4.3: The role of businesses **Levien room**

Moderator: **Yuki Numata**, RMI (USA), Rapporteur: Karl Scheifinger, IIASA (Austria)

Session content: Group discussion about how can research help move the needle on corporate (& policy) action on LED.

- The role of business solutions: corporate action on material and energy efficiency

Yuki Numata, RMI (USA)

- Diffusion of social innovations

Greg Nemet, Wisconsin Energy Institute (USA) and Charlie Wilson, Oxford University (UK)

- Climate-Tech Innovation Finance from Japanese Energy-Startup Investors' Perception

Hiroyoshi Iwata, Tokyo University (Japan)

- The role of data center operators & tech companies in managing AI energy use

Eric Masanet, University of California (USA)

17:30-18:00 Welcome drink **Kaiserbahnhof**

18:00-19:30 Dinner

20:00 Shuttle Bus departing from Kaiserbahnhof Laxenburg to Motel One (see Logistic Note for more information)

****

CORE DAY: DAY 2 – 9 October, Wednesday

08:00 **Shuttle bus** pick-up from Vienna (see Logistic Note for map)

09:00-10:00 Session 5. High-with-Low policy [Plenary session] Gvishiani room

Moderator: **Shonali Pachauri**, IIASA (Austria), Rapporteur: Enrico Cofler, CMCC (Italy)
The session connects EDITS work with similar concepts in policies and behavior research.

09:00-09:20 New European Bauhaus initiative, **John Schellnhuber**, IIASA (Austria)
09:20-09:40 Low energy lifestyles and their policy implementation, **Halliki Kreinin**, RIFS Potsdam (Germany)
09:40-10:00 General discussion on:

- What (existing or future) policies facilitate LED transformation
- Who in the policy-making should EDITS connect with
- What are the key messages from demand-side research for successful relevant policies

10:00-10:30 Coffee break

10:30-12:00 Session 6. Break-out Groups on IPCC impact

BOG 6.1: EDITS brings to IPCC… Gvishiani room

Moderator: **Keywan Riahi,** IIASA (Austria), Rapporteur: Paul Kishimoto, IIASA (Austria)

Session content: identifying EDITS' key entry points to IPCC AR7 and special reports, including content and format.

BOG 6.2: EDITS brings to IPCC… Wodak room

Moderator: **Joyashree Roy,** AIT (Thailand), Rapporteur: Ninaad Desai, AIT (Thailand)

Session content: identifying EDITS' key entry points to IPCC AR7 and special reports, including content and format.

12:00-14:00 Lunch break Schlossrestaurant

14:00-15:15 Session 7. Policy Break-out Groups

These Break-out-Groups (BOGs) focus on specific areas closely related to the practical and policy aspects of the demand-side and allow for group discussions.

BOG 7.1: Cities Gvishiani room

Moderator: **Leila Niamir**, IIASA (Austria) and **Felix Creutzig**, MCC (Germany),Rapporteur:Jubair Sieed, RITE (Japan)

Session content: Group discussion about the urban environment and cities in relation to the IPCC report on cities

BOG 7.2: Demand across sectors: Decent Living Standards Wodak room

Moderator: **Dominik Wiedenhofer**, BOKU (Austria), Rapporteur: Andé Baumgart, BOKU (Austria)

Presentations (10 mins) followed by discussion

- Global demand for the building material stocks of 1.8 million individual settlements: North-South disparities and knowledge gaps

Tomer Fishman, Leiden University (the Netherlands)

- Pathways to a net zero building sector in Colombia: insights from a circular economy perspective

Johan Vélez Henao, University of Freiburg (Germany)

- Minimal material stock increases needed to achieve global decent living standards in time for UN SDGs

Jan Streek, BOKU (Austria)

- Closing decent living gaps in energy and emissions scenarios

Jarmo Kikstra, IIASA (Austria)

- Swiss DLS and inequality [TBC]

Joel Millward-Hopkins, University of Leeds (UK)

15:15-15:30 Reporting back [Plenary session] Gvishiani room

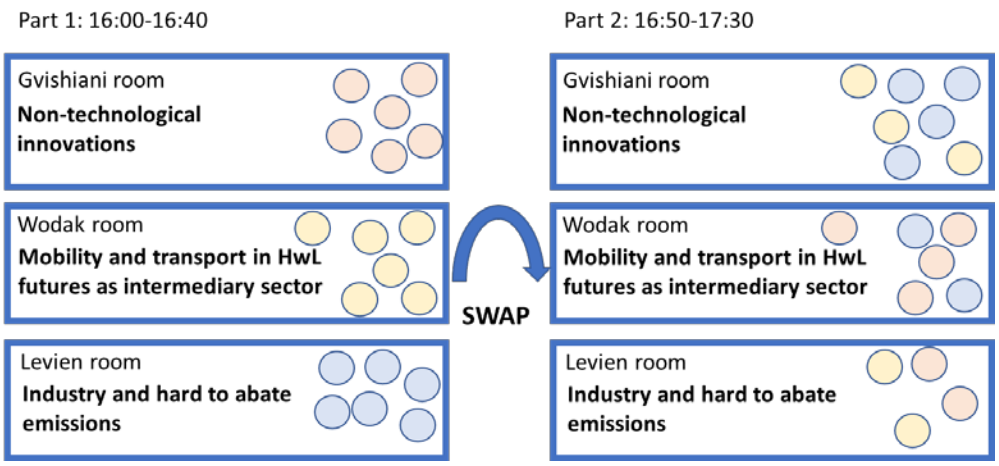
Reporting back from the BOGs along the day, focusing on strategies for IPCC impact.

Moderator: **Diana Ürge-Vorsatz,** CEU (Austria)

15:30-16:00 Coffee break

16:00-17:30 Session 8. Research presentations of the community: rolling flash-talks

EDITS activities are closely linked to the core research activities of its members. The value of EDITS lies in combining the power of the network with on-going daily research, leading to shared outputs, new concepts, novel ideas, reformulated methods. This session hosts flash-talks on relevant on-going research within and outside of EDITS.



The session is divided into two parts of 40 minutes and takes place in three parallel rooms each hosting 3-4 presenters. The speakers will do their presentation twice, each with a different audience. This means 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.

Non-technological innovations Gvishiani room

Moderator: **Kaveri Ashok**, CSTEP (India), Rapporteur: Jan Streek, BOKU (Austria)

- Navigating Tensions and Trade-offs in Structural Change for Wellbeing and Sustainability Transitions
  Nuno Bento, ISCTE (Portugal)
- Digitalization of daily life
  Poornima Kumar, Oxford University (the UK)
- Social innovation enablers to unlock a low energy demand future
  Elena Verdolini, CMCC (Italy)
- A model and interactive calculator to aggregate demands of climate mitigation proposals
  Jennifer Hawkin, University of Cambridge (the UK)

Mobility and transport in HwL futures as intermediary sector Wodak room

Moderator: **David Mccollumn**, ORNL (USA), Rapporteur: **Maximilian Forberg**, Chalmers (Sweden)

- What is decent mobility, how to deal with heterogeneity
  Marlin Arnz, Technical University Berlin (Germany)
- Latest PASTA results relevant for EDITS
  Luis Martinez, OECD-ITF (France)
- Impacts of working from home on household energy demand including automobile fuel: An analysis using official statistics of Japan
  Ayami Hayashi, RITE (Japan)
- Implications of shared mobility on vehicle fleet turnover - a semi-empirical model based on Swedish statistics
  Johannes Morfeldt, Chalmers University of Technology (Sweden)

Industry and hard to abate emissions **Levien room**

Moderator: **Gamze Ünlü**, IIASA (Austria), Florian Maczek, IIASA (Austrria)

- Hard to abate sectors and negative emissions
  Oreane Edelenbosch, Utrecht University (the Netherlands)
- Industry decarbonization in China
  Nan Zhou, LBNL (USA)
- Carbon Footprint and Economic Analysis of China's Ammonia Energy
  Ou Xunmin, Tsinghua University (China)
- Analyzing Low Energy Demand Scenarios: CGE and Index Decomposition with Climate Change Impact Assessment
  Tae Yong Jung, Yonsei University (South Korea)

17:45 Shuttle Bus departing from IIASA to Motel One (see Logistic Note for more information)

****

CORE DAY: DAY 3 – 10 October, Thursday

08:00 **Shuttle bus** pick-up from Vienna (see Logistic Note for map)

09:00-10:30 Session 9. Model Complementarity Exercise [Plenary session] **Gvishiani room**

The Working Group Protocol has had a very active time during 2023-24 to enable the development of new scenarios and to make the complementarity exercise tangible. The MCE has focused on mobility, and it will be expanded to other sectors step-by-step. In this session, we will discuss the progress and lessons so far, as well as plan ahead.

Moderator: **Volker Krey**, IIASA (Austria), Rapporteur: **Zakia Soomauroo**, Reiner Lemoine Institut (Germany)

09:00-09:10 Framing the LED scenario development in EDITS
Bas van Ruijven, IIASA (Austria)

09:10-09:20 Expanding the LED/HwL scenario family: A case of mobility
Masa Sugijama, University of Tokyo (Japan)

09:20-09:30 Reminder of what LED and HwL really are
Arnulf Grübler, IIASA (Austria)

09:30-09:40 What is LED in India: lessons from India DLE fast-track
Alessio Mastrucci, IIASA (Austria)

09:40-10:30 Plenary discussion on:

- How to take LED into pieces - e.g. sectors, social-climate-economic policy targets, techno vs. social innovation. There is not always an energy reduction
- What are key drivers of the mobility sector for LED (considering what is included now and in the future)
- How and why can MCE work (linking diff. models, data flow (output->intput), comparing, etc.)

10:30-11:00 Coffee break

11:00-12:00 Session 10. Scenario Break-out Groups

These Break-out-Groups (BOGs) focus on scenarios and how to progress with the MCE.

BOG 10.1: Transport scenarios **Gvishiani room**

Moderator: **Masa Sugiyama**, University of Tokyo (Japan); Rapporteur: **Tao Cao**, University of Tokyo (Japan)

Presentations (5-10 mins) followed by discussion

- MCE transport model: Message Transport

Paul Kishimoto, IIASA (Austria)

- MCE transport model: DNE21+

Keigo Akimoto and Fuminori Sano, RITE (Japan)

- MCE transport model: PASTA

Luis Martinez, OECD-ITF (France)

- Technical and economic modelling of last-mile transport: A case for Brazil

Roberto Schäffer, COPPE (Brazil)

- How the assumptions of transport demand share affect the outcome of upstream energy systems

Takuya Hara, IIASA (Austria)

BOG 10.2: Aspects of LED scenarios **Wodak room**

Moderator: **Charlie Wilson,** Oxford University (the UK), Rapporteur: **Johan Vélez Henao**, Uni. Freiburg (Germany)

Presentations (15 mins) and discussions

- Overview of the demand-side model comparison by ECEMF project for transport, buildings and industry

Lukas Kranzl, TUW (Austria)

- Desprawl scenarios

Sascha Nick, EPFL (Switzerland)

- Bottom-up energy demand estimation for India using PIER

Sreenivas Ashok, Prayas (India)

- DLS-High tech Scenario using TREES

Yoshiyuki Shimoda, Osaka University

12:30-13:30 Session 11. Closing plenary **Gvishiani room**

Moderator: **Benigna Boza-Kiss and Bas van Ruijven**, IIASA (Austria)

Session content: Conclusions from the meeting

13:30-14:30 Lunch break **Corridor and Wodak room**

Side-events

15:00-16:00 WG Data meeting (open) **Gvishiani room**

16:00-17:30 FT costs and benefits data (closed) **Gvishiani room**

16:00-17:00 FT24-4 Decent mobility (open) **Wodak room**

17:00-18:00 FT24-4 Decent mobility (closed) **Wodak room**

17:45 Shuttle Bus departing from IIASA to Motel One (see more in Logistic Note)

SIDE-EVENT DAY: 11 October, Friday

08:30 Public transport pool to IIASA (see Logistic Note, look for colleagues to travel together)

9:00-12:00 WG Wellbeing (open) **Wodak room**

12:00-14:00 LUNCH (at own costs)

14:00-16:00 FT24-1 Well with Low (closed) **Gvishiani room**

2024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

都市エネルギーシステム領域

世界規模での気候変動緩和に向けて，エネルギー供給側の脱炭素化だけでなくエネルギー需要側の削減が重要である．運輸部門ではモビリティシステムの転換に伴うエネルギーサービスの形態の劇的な変化，また業務部門においてはテレワークの普及や小売業のデジタル化に伴って，大幅なエネルギー需要の削減が起こりうる．その一方で家庭部門におけるエネルギー需要は冷暖房や調理などといった人間の衣食住を直接的に支えるサービスに起因するため，業務・運輸部門と同等の劇的な削減が期待しづらい．さらに今後世界の人口が増加していくことで人々の「well-being」を保障するために必要なエネルギーは増大していく．これらの要因により，今後，エネルギー需要全体に占める家庭部門の相対的な重要性が増していくと考えられる．したがって世界規模で長期的に低エネルギー社会を計画するにあたり，家庭部門のエネルギー需要を把握し，工学的な削減の可能性を探ることが重要であるといえる．

このような背景から、日本全国を対象として開発されてきたボトムアップ型の家庭部門最終エネルギー需要予測モデル[1)]（Total Residential End-use Energy Simulation：以下，TREES モデル)の推計対象を世界各国に拡張し、TREESモデルを「日本におけるトップランナー相当の高効率機器を用いて全世界人口のDLS(Decent Living Standards)を満たす」という想定の「DLS+HighTechシナリオ」に基づいて運用することで，世界の人々が「well-being」な生活を営むために最低限必要なエネルギー需要を推計した．さらに，家庭部門のエネルギー消費用途の中で，大きな割合を占める冷暖房・給湯需要については，外気温と比較することによって推計結果の検証を行った．本検討内容は次の通り第41回エネルギー・資源学会エネルギーシステム・経済・環境コンファレンス講演論文集において報告した．

- 石原沙莉，五味勇心，正野景大，内田英明，下田吉之：世界の家庭部門エネルギー最終需要推計に関する研究～第1報　計算条件設定と推計結果について～，第41回エネルギー・資源学会エネルギーシステム・経済・環境コンファレンス講演論文集，pp. 257-262，2025年1月
- 五味勇心，石原沙莉，正野景大，内田英明，下田吉之：世界の家庭部門エネルギー最終需要推計に関する研究　～第２報　計算条件の感度解析および既往研究等との推計結果比較～，第41回エネルギー・資源学会エネルギーシステム・経済・環境コンファレンス講演論文集，pp. 263-268，2025年1月

加えて、LEDシナリオで描かれている大幅なエネルギー需要の削減を建築分野において実現す

るための建築性能シミュレーションの役割について、下記の論文に取りまとめた。

- Shimoda, Y. (2024). The role of building performance simulations in citywide and national global warming mitigation policy. *Journal of Building Performance Simulation*, 1–6. https://doi.org/10.1080/19401493.2024.2421327

以降、上記論文を示している。

参考文献

1) Yoshiyuki Shimoda, Misaki Fujiwara, Toshiki Nakanishi, Yohei Yamaguchi, Hideaki Uchida; Energy and carbon management system for a city and a nation, ECEEE 2022Summer Study Proceedings (2022).

2025.1.28～29
第41回エネルギーシステム・
経済・環境コンファレンス
講 演 論 文 集

世界の家庭部門エネルギー最終需要推計に関する研究 ～第1報　計算条件設定と推計結果について～

Research on the Global Simulation of Final Energy Demand in the Residential Sector Report 1: Calculation Conditions and Estimation Results

石原沙莉*・五味勇心*・正野景大*・内田英明*・下田吉之*
Sari Ishihara　Yushin Gomi　Keita Shono　Hideaki Uchida　Yoshiyuki Shimoda

Abstract
This study expands the TREES bottom-up energy demand model, originally developed for Japan, to a global context using the "DLS+HighTech Scenario." This scenario assumes the deployment of Japan's top-tier efficient appliances to achieve Decent Living Standards (DLS) for the global population, thereby estimating the minimum energy required for worldwide well-being. In this first report, the per capita Decent Living Energy (DLE) was estimated for 98 countries based on the DLS+HighTech scenario. Furthermore, the alignment of each country's DLE with outdoor temperatures was analyzed, focusing on heating, cooling, and water heating—key contributors to residential energy consumption. The analysis identified a positive correlation between cooling demand and outdoor temperature, and a negative correlation for heating and water heating. For countries that exhibited deviations from these trends, further investigation attributed the differences to unique characteristics of their outdoor temperature profiles. The second report conducts sensitivity analysis and compares TREES estimates with previous studies and statistics.
Key words: Global Warming, Global Energy Demand, Bottom-up Simulation, Decent Living Standard

１．緒論

世界規模での気候変動緩和に向けて，エネルギー供給側の脱炭素化だけでなくエネルギー需要側の削減が重要である．運輸部門ではモビリティシステムの転換に伴うエネルギーサービスの形態の劇的な変化，また業務部門においてはテレワークの普及や小売業のデジタル化に伴って，大幅なエネルギー需要の削減が起こりうる．その一方で家庭部門におけるエネルギー需要は冷暖房や調理などといった人間の衣食住を直接的に支えるサービスに起因するため，業務・運輸部門と同等の劇的な削減が期待しづらい．さらに今後世界の人口が増加していくことで人々の「well-being」を保障するために必要なエネルギーは増大していく．これらの要因により，今後，エネルギー需要全体に占める家庭部門の相対的な重要性が増していくと考えられる．したがって世界規模で長期的に低エネルギー社会を計画するにあたり，家庭部門のエネルギー需要を把握し，工学的な削減の可能性を探ることが重要であるといえる．

筆者らは，日本全国を対象として開発されてきたボトムアップ型の家庭部門最終エネルギー需要予測モデル [1] (Total Residential End-use Energy Simulation : 以下, TREES モデル)の推計対象を世界各国に拡張した．TREES モデルは，現実の家庭でエネルギーが消費されるプロセスを可能な限り忠実に再現しており，気象や居住者行動に基づいて機器の稼働を模擬し，機器のエネルギー需要を積み重ねて世帯のエネルギー需要推計を行う．特に，冷暖房のエネルギー消費は気象データ，代表住宅の間取り，外壁の仕様等を入力条件として，動的熱負荷計算を行うことにより高精度に推計が可能である．本研究では，TREES モデルを「日本におけるトップランナー相当の高効率機器を用いて全世界人口の DLS（Decent Living Standards）を満たす」という想定の「DLS+HighTech シナリオ」に基づいて運用することで，世界の人々が「well-being」な生活を営むために最低限必要なエネルギー需要を推計した．さらに，家庭部門のエネルギー消費用途の中で，大きな割合を占める冷暖房・給湯需要については，外気温と比較することによって推計結果の検証を行った．続く既往研究や統計値との比較および感度解析の結果については，第 2 報 [2]を参照されたい．

２．既往研究

Mastrucci ら [3]は，Global South で冷房を利用できず熱ストレスにさらされうる人口の分布を特定し，冷房アクセスギャップを解消するのに必要なエネルギー需要を推計している．

Kikstra ら [4]は，健康，住宅，栄養，社会活動，移動手段に関する DLS を定義し，世界各国で DLS と現状のエネルギー需要のギャップを評価した．住宅に関しては，冷暖房に加えて家電機器や給湯についても DLS を設定し，包括的

*大阪大学大学院工学研究科環境エネルギー工学専攻
〒565-0871 大阪府吹田市山田丘 2-1-M3 棟 3 階
E-mail：ishihara@ue.see.eng.osaka-u.ac.jp

なエネルギー需要推計を行っている．

いずれの既往研究にも，共通して 2 点の課題がある．1 点目は冷暖房(エアコン)のエネルギー需要推計手法である．両既往研究において，冷暖房のエネルギー需要はデグリーデー法により求めた必要処理熱量を一定のエネルギー効率で割ることによって算出しているが，デグリーデー法の精度は十分に検証されておらず，さらにエアコンのエネルギー効率は外気温や負荷に応じて一定ではない．また推計に使用する環境条件については，日射熱取得量を月単位，外気温度を日単位で取得しておりデータの時間粒度が低い．2 点目は世帯のエネルギー消費の不均一性の考慮である．両既往研究において，冷暖房エネルギー需要は床面積あたりエネルギー消費量に一人当たり床面積と人口を乗じることで算出している．家庭用エネルギー消費は冷暖房をはじめとして，世帯構成員の間で共有することで一人当たりのエネルギー消費量を低下させやすいものが多いが，人口一人あたりの推計ではこの影響を評価できない．

本研究では，5 分単位の環境条件を考慮して，エアコンのエネルギー効率の変動を再現し，冷暖房エネルギー需要を高精度に推計する．また，世帯単位でエネルギー需要推計を行うことで国による人口動態の違いを反映する．

3．手法

3.1 世帯類型

TREES モデルによって，各国の気象データを入力し**表 1** に示す 12 の世帯類型のエネルギー需要を推計し，その結果に各国の類型別世帯数を乗じることで家庭部門エネルギー最終需要を推計した．各国の類型別世帯数は，世帯人数別世帯数に世帯人数別戸建住宅居住比率を乗じることで算出した．

表 1　世帯類型

世帯類型	世帯人数	家族構成	住宅種別
1	1	単身	集合
2	1	単身	戸建
3	2	夫婦	集合
4	2	夫婦	戸建
5	3	夫婦＋子 1 人	集合
6	3	夫婦＋子 1 人	戸建
7	4	夫婦＋子 2 人	集合
8	4	夫婦＋子 2 人	戸建
9	5	夫婦＋子 3 人	集合
10	5	夫婦＋子 3 人	戸建
11	6	夫婦＋子 4 人	集合
12	6	夫婦＋子 4 人	戸建

(1) 世帯人数別世帯数

世帯人数別世帯数は国連統計局が発行している Demographic Yearbook System[5]から得ることができる．**図 1** に一部の国々の世帯人数別世帯数を示す．世帯人数構成は国によって大きく異なっているが，先進国は平均世帯人数が小さく，発展途上国では大きい傾向がある．また，このデータは各国政府が独自に行っている人口センサスのデータを集計しているため，すべての国を網羅しておらず，調査年も一貫していない．そこで，世帯数及び世帯人数構成には 10 年程度で極端な変化はないと考え，2009 年以降のデータを得られる 96 か国を最初の推計対象とした．また，人口の多い国として，インド（2001 年調査）とエチオピア（2007 年調査）のデータも加え，最終的に計 98 か国のエネルギー消費量推計を行った．ただし，6 persons and over（6 人以上）の世帯に関しては，TREES モデルの制約上，6 人世帯として推計を行った．

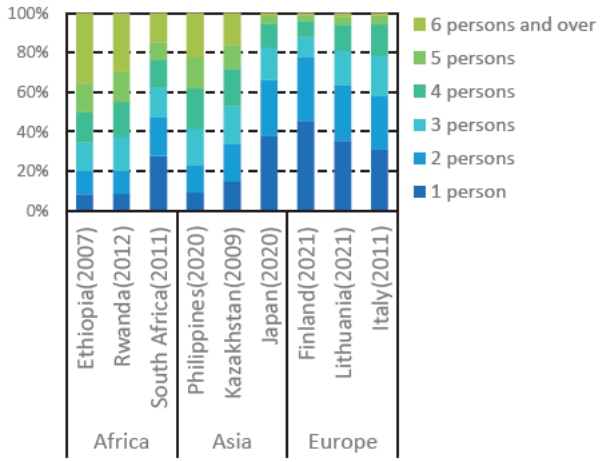


図 1　世帯人数別世帯数（抜粋）

(2) 世帯人数別戸建住宅居住比率

戸建住宅居住比率は，地球環境産業技術研究機構(以下，RITE）から提供を受けた．53 地域区分別の 2020 年戸建住宅居住人口比率の推計結果の一部を**図 2** に示す．また，本研究室が日本の家庭部門エネルギー需要推計にあたって国勢調査をもとに回帰分析によって作成した世帯分布を**図 3** に示す．日本において，単身世帯では集合住宅居住世帯の方が戸建住宅居住世帯より多い（戸建住宅居住比率 32%，集合住宅居住比率 68%）が，2 人～6 人以上世帯では逆転している．この傾向は他国にも共通していると考え，すべての国で単身世帯の戸建住宅居住比率を 32%とし，各国の 2 人～6 人以上世帯の戸建住宅居住比率　r_{2h-6h}は式(1)によって算出した．

$$r_{2h-6h} = \left(r_p \sum_1^6 iN_i - 0.32N_1\right) \Big/ \sum_2^6 iN_i \qquad (1)$$

ここで,

r_p：戸建住宅居住人口比率

i：世帯人数

N_i：世帯人数 i の世帯数

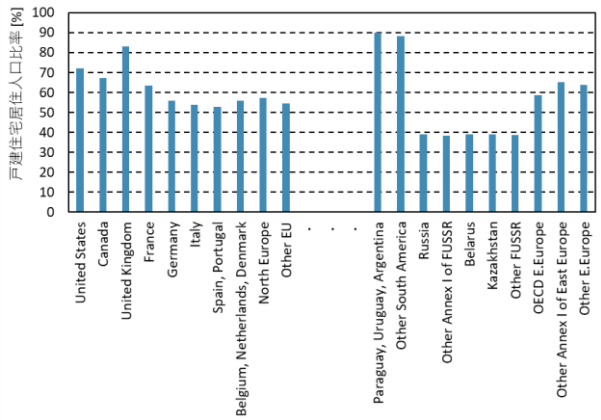


図 2　地域区分別　戸建住宅居住人口比率

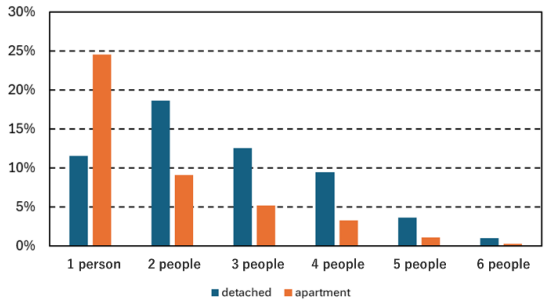


図 3　日本の戸建・集合居住世帯比率推計結果

3.2 居住者行動

TREES モデルの構成要素の一つとして，各居住者の 1 年分の生活行為を 5 分間隔で生成する生活行為生成モデル [6] が開発されている．本モデルは，平成 18 年に日本で実施された社会生活基本調査の生活時間に関する結果に基づいて，各居住者の属性によって生活行為を再現する．例として，**図 4** に全居住者属性の平均的な時刻別行為実施確率を示す．本研究では各世帯類型について標準的な世帯属性を設定し，生活行為生成モデルによって居住者行動を模擬した．ここで，全世帯類型の成人をフルタイム就業者と設定している．全ての国において，この日本人の行動スケジュールを使用して推計を行った．

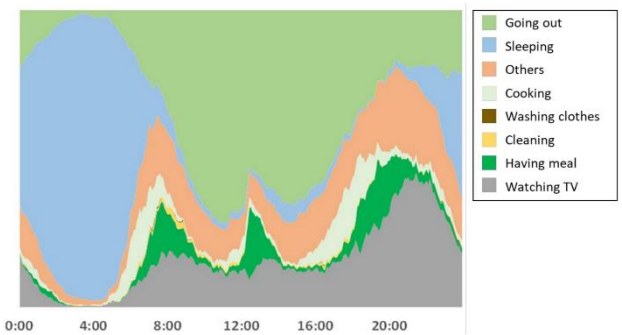


図 4　時刻別行為実施確率

3.3 気象

本研究では TREES モデルに入力する気象データとして各国の代表都市における 2007 年から 2021 年までの 15 年間の気象データから作成された典型気象データ [7]を用いた．この典型気象データは，月ごとに 15 年のうちで最も標準的な年を選び出して構成された気象データである．本研究では，各国を代表する都市を選定し，その都市の気象データを用いて国全体のエネルギー消費量を推計した．以下に，各国における気象データの代表都市の選定方法および TREES モデルの条件設定の一つである冷暖房期間の設定方法について説明する．

(1) 代表都市の選定

原則として，総務省統計局の「世界の統計 2024」[8]に基づき各国で最も人口の多い都市を代表都市とした．「世界の統計 2024」にデータが無い国については，その国の首都を代表都市とした．

(2) 冷暖房期間の設定

TREES モデルでは，暖房および冷房の稼働条件を設定するために冷暖房期間が事前に用意される必要がある．本研究では，各国の気温データをもとに冷暖房期間を設定した．例えば日本の場合，代表都市である東京の気温データから**図 5** のように暖房期間と冷房期間を設定した．

冷房使用の目安となる日平均気温として 28℃を，暖房使用の目安となる日平均気温として 14℃を想定し，28℃を上回る期間は冷房期間，14℃を下回る期間は暖房期間とした．ただし，**図 6** のフランスの例のように 28℃を上回る日が 1 日～3 日しかない場合には冷房は稼働しないものと考え，冷房期間は出現しないこととした．これは暖房期間についても同様で，14℃を下回る日が 1 日～3 日しかない場合，暖房期間は出現しないこととした．冷房期間と暖房期間の間については，その前後の期間に合わせて目視で判断して暖房期間または冷房期間に分配した．同様の設定を各国の気温データをもとに行い，冷暖房期間とした．

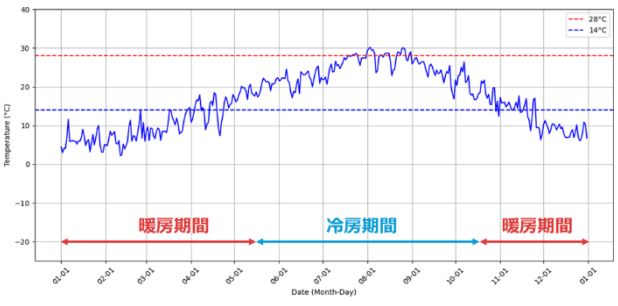


図 5　日本（東京）の冷暖房期間

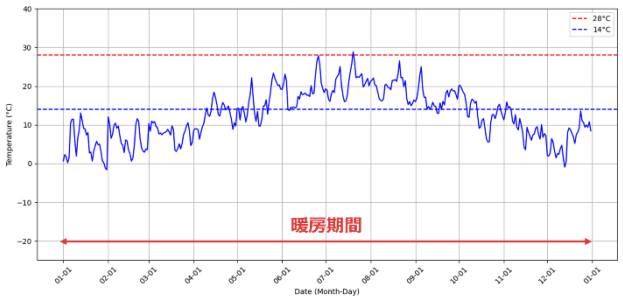


図 6　フランス（パリ）の冷暖房期間

3.4 DLS+HighTech シナリオ

本研究では DLS+HighTech シナリオを作成し，世界中のすべての人々に DLS を提供するために必要な最低限度の家庭部門エネルギー需要を推計した．DLS+HighTech シナリオでは「世界中のすべての人々が DLS を享受しつつ，日本におけるトップランナー相当の高効率機器によって省エネルギーが実現されている」という想定をしている．DLS+HighTech シナリオの設定の概要を**表 2** に示す．

住宅，給湯，冷蔵庫，テレビ，調理機器の DLS の設定条件は Kikstra ら[4]をもとに設定した．冷暖房についても，「稼働する時間帯・部屋は制限しない」という条件以外は Kikstra ら[4]に基づいている．

表 2　DLS+HighTech シナリオの設定

	DLS	HighTech
住宅	住宅類型：「最低 10m2/人・3 人世帯までは最低 30m2」の条件をもとに決定	断熱性能：寒冷地では日本の ZEH 基準，温暖な地域では日本の 1999 年基準相当など，国によってエネルギー最小となる仕様を決定
冷暖房	RAC 全部屋に 1 台 冷房設定温度 26℃ 暖房設定温度 20℃ 相対湿度 60% 稼働する時間帯・部屋は制限しない	製造年区分：最新（2016-2020） 冷暖房能力：各部屋の床面積によって最適なものを設定
給湯	給湯を必要とする行為はシャワーのみ 給湯温度 40℃	電気ヒートポンプ式給湯器
照明	全室に設置	LED
冷蔵庫	世帯当たり 1 台 容量：148L	年間消費電力 229kWh（Haier 製）
テレビ	世帯当たり 1 台	製造年区分：最新 サイズ：最小（-15 インチ） タイプ：液晶
調理機器	世帯当たり 1 台	IH ヒーター

4．結果

4.1 冷暖房・給湯

(1) ヒートマップ

TREES モデルを用いて推計した，DLS+HighTech シナリオの冷房・暖房・給湯の一人あたり年間二次エネルギー消費量を**図 7** から**図 9** に示す．グレーで色付けされている国々については，世帯データが得られなかったため今回エネルギー消費量推計を行っていない．また，**図 10** に年間平均外気温を示す．平均外気温が高い低緯度帯ほど冷房エネルギー需要が大きく，平均外気温が低い北半球の高緯度帯ほど暖房及び給湯のエネルギー需要が大きいという傾向が確認できる．次節以降，冷暖房・給湯について，世帯類型 1（単身・集合住宅居住）の年間エネルギー消費量と年間平均外気温との相関を確認する．

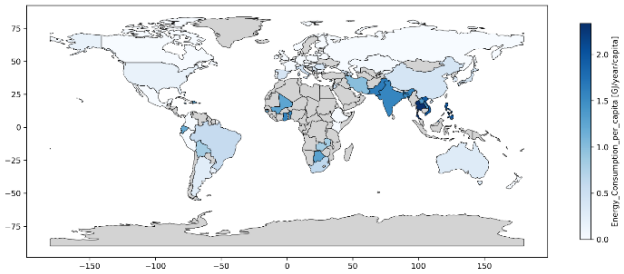


図 7　冷房一人当たり年間二次エネルギー消費量

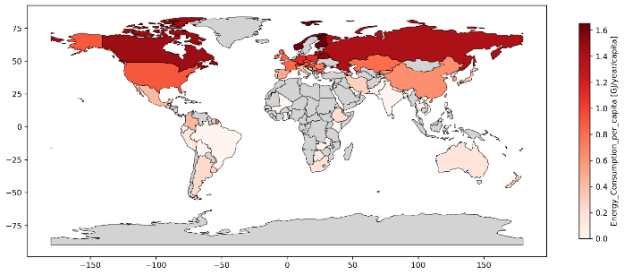


図 8　暖房一人当たり年間二次エネルギー消費量

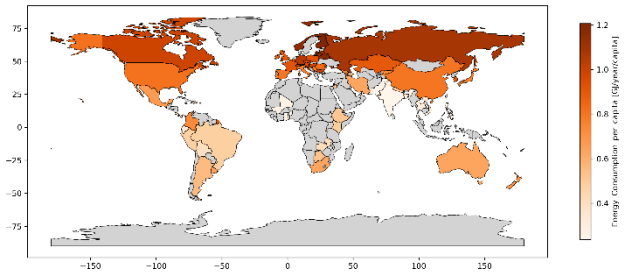


図 9　給湯一人当たり年間二次エネルギー消費量

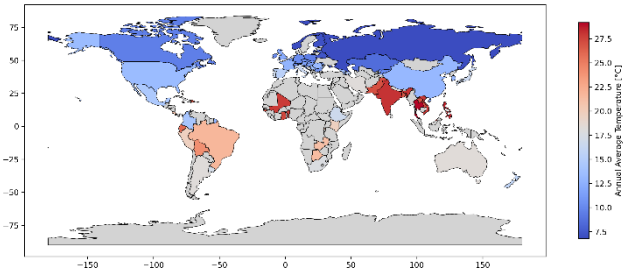


図 10　年間平均外気温

(2) 冷房需要と年間平均外気温の相関

図 11 に冷房エネルギー需要と年間平均外気温との相関を示す．冷房需要は平均外気温に対して正の相関を示しているが，Botswana は他国の傾向から大きく外れており，平均気温が同程度の Zambia 及び Mauritius より冷房需要が極めて大きい．そこで，**図 12** から**図 14** にこれら 3 か国の気温の年間推移を 5 分単位で示す. Botswana の気温は Zambia 及び Mauritius と比べて変動が大きく，夏季の気温は冷房設定温度である 26℃を大きく超えているため，結果として冷房需要が大きくなったと考えられる．

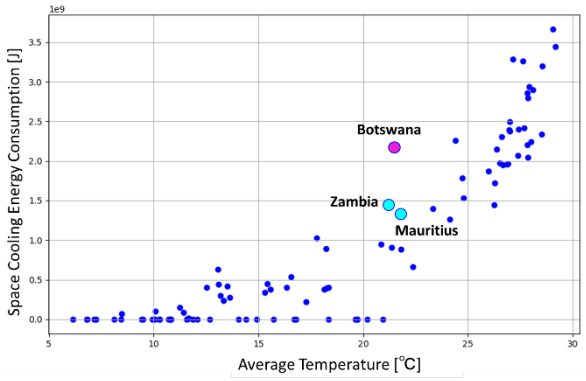


図 11　冷房需要と年間平均外気温

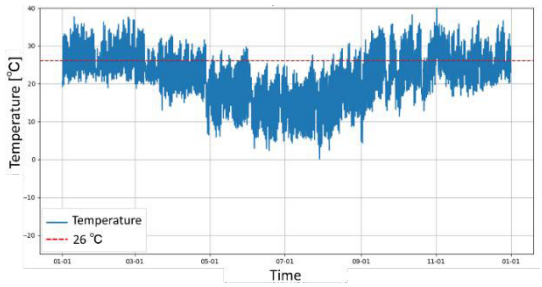


図 12　Botswana の外気温の年間推移

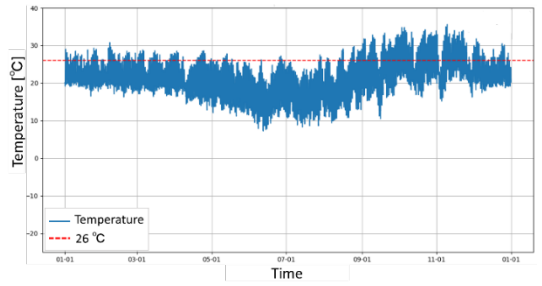


図 13　Zambia の外気温の年間推移

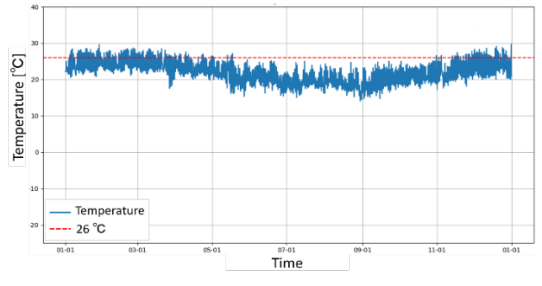


図 14　Mauritius の外気温の年間推移

(3) 暖房需要と年間平均外気温の相関

図 15 に暖房エネルギー需要と年間平均外気温との相関を示す. 暖房需要は平均外気温に対して負の相関を示した．Kazakhstan，Kyrgyzstan，China，Korea は他国の傾向から外れている．これらの国々は年間平均外気温が同程度の国に比べ暖房の稼働を必要とする期間が短いため，暖房需要が小さくなったと考えられる．

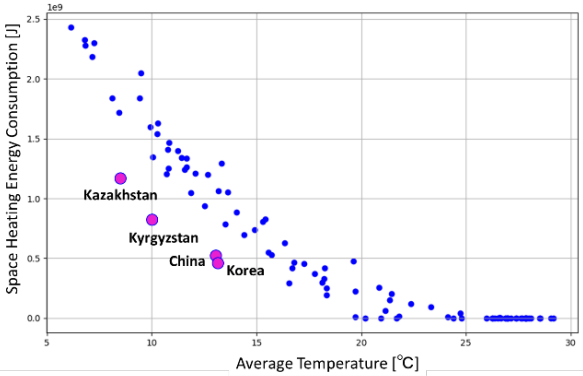


図 15　暖房需要と年間平均外気温

(4) 給湯需要と年間平均外気温の相関

図 16 に給湯エネルギー需要と年間平均外気温との相関を示す．給湯需要は外気温に対して線形な負の相関を示した．これは TREES モデルにおいて給湯需要が上水温度に基づいて算出され，上水温度は当日・過去 5 日間・過去 7 日間の平均外気温を説明変数とする重回帰式で算出されるためである．

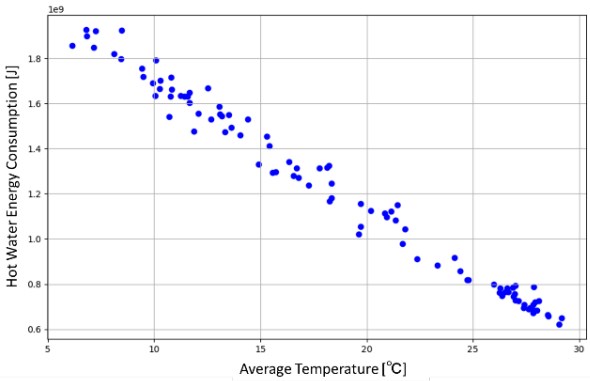


図 16　給湯需要と年間平均外気温

4.2 全用途

図 17 に一人あたり年間二次エネルギー消費量の DLS+HighTech シナリオ推計結果を示す．一人あたりの DLS を満たす最小エネルギー需要（Decent Living Energy: 以下，DLE）は，1.1 GJ/capita ～ 3.8 GJ/capita まで開きがある. DLS+HighTech シナリオにおいて，家電のエネルギー消費量の国間の差が小さいため，DLE の差は，冷暖房・給湯需要と世帯構成人数よって決定づけられる．北半球の高緯度帯で一人あたりエネルギー需要が最も大きいが，これは暖房及び給湯のエネルギー需要が大きいことに加え，平

均世帯人数が小さいことが影響している．

５．まとめ

本研究では，動的熱負荷計算による高精度な冷暖房エネルギー需要推計が可能である，ボトムアップ型の TREES モデルを用いて，世界 98 か国の DLE を推計した．高い時間粒度で，世帯のエネルギー消費量の不均一性を考慮した推計を行うことができた．さらに，家庭部門のエネルギー需要の中で非常に大きな割合を占める冷暖房・給湯需要に関して，外気温との整合性を確認した．検証の結果，冷房は外気温に対して正の相関，暖房･給湯は負の相関を示した．他国の傾向とはずれる国については詳細に分析を行い，各国の外気温の特性によるものだと結論付けた．また，全用途の一人あたりエネルギー消費量においては，世帯構成人数の影響が見られる．このことからも，家庭部門において高精度な推計を行うには，エネルギー消費単位である世帯ごとに推計を行うことで，世帯の不均一性や世帯における機器の共有の影響を考慮することが重要だといえる．

今後は，今回推計を行わなかった国についても世帯のデータを整備し，全ての国で DLS+HighTech シナリオに基づくエネルギー需要推計を行う．さらに米国や中国といった面積の大きな国については，気象を 1 都市で代表させるのではなく，いくつかの地域に分割して推計を行うことによって推計精度を向上させる．また，居住者の生活行動に関しては，共働き世帯だけでなく方働き世帯を考慮することによって，より現実に即した DLE を推計する．

謝辞

本研究は RITE および IIASA が運営する EDITS（Energy Demand changes Induced by Technological and Social innovations）プロジェクトの支援を受け実施された．

参考文献

1) Yoshiyuki Shimoda, Misaki Fujiwara, Toshiki Nakanishi, Yohei Yamaguchi, Hideaki Uchida; Energy and carbon management system for a city and a nation, ECEEE 2022 Summer Study Proceedings (2022).

2) 五味勇心，石原沙莉，正野景大，内田英明，下田吉之; 世界の家庭部門エネルギー最終需要推計に関する研究～第 2 報　計算条件の感度解析および既往研究等との推計結果比較～，第 41 回エネルギーシステム・経済・環境コンファレンス, 11-1 (2024).

3) Alessio Mastrucci, Edward Byers, Shonali Pachauri, Narasimha D. Rao; Improving the SDG energy poverty targets: Residential cooling needs in the Global South, Energy and Buildings, 186(2019), pp.405-415.

4) Jarmo S Kikstra, Alessio Mastrucci, Jihoon Min, Keywan Riahi, Narasimha D Rao; Decent living gaps and energy needs around the world, Environmental Research Letters, 16(2021), 095006.

5) UNSD; Demographic Yearbook System https://unstats.un.org/unsd/demographic-social/products/dyb/#censusdatasets （アクセス日 2024.08.26）

6) 岡田 健志，正田 悠人，今井 達也，山口 容平，下田吉之; 居住者属性を考慮した住宅居住者生活行為確率生成モデル，エネルギー・資源学会論文誌，42-6 (2021) , pp.403-412.

7) Lawrie, Linda K, Drury B Crawley. 2022. Development of Global Typical Meteorological Years (TMYx). https://climate.onebuilding.org/ （アクセス日 2024.08.26）

8) 総務省統計局；世界の統計 2024，(2024).

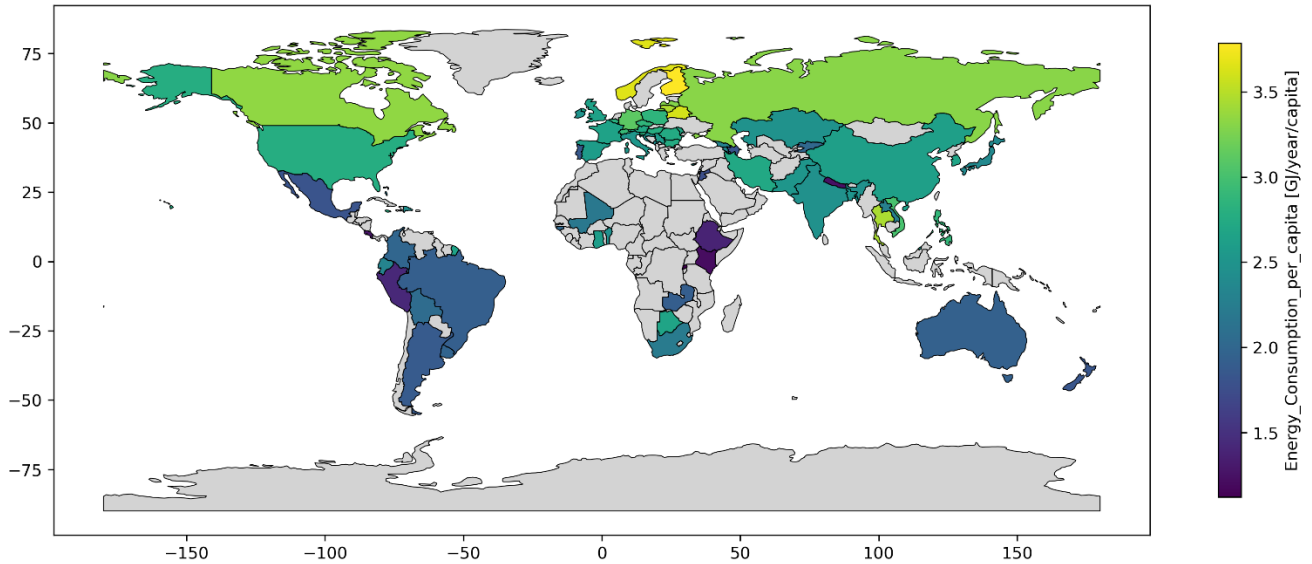


図 17　一人あたり年間二次エネルギー消費量

2025.1.28～29
第41回エネルギーシステム・
経済・環境コンファレンス
講 演 論 文 集

世界の家庭部門エネルギー最終需要推計に関する研究 ～第 2 報　計算条件の感度解析および 既往研究等との推計結果比較～

Research on the Global Simulation of Final Energy Demand in the Residential Sector Report 2: Sensitivity Analysis of Estimation Conditions and Comparison of Results with Previous Studies

五 味 勇 心 *・ 石 原 沙 莉 *・ 正 野 景 大 *・ 内 田 英 明 *・ 下 田 吉 之 *
Yushin Gomi　Sari Ishihara　Keita Shono　Hideaki Uchida　Yoshiyuki Shimoda

Abstract
This study expands the TREES bottom-up energy demand model, originally developed for Japan, to a global context using the "DLS+HighTech Scenario." This scenario assumes the deployment of Japan's top-tier efficient appliances to achieve Decent Living Standards (DLS) for the global population, thereby estimating the minimum energy required for worldwide well-being. While the first report has validated relative energy demands across countries based on climate data, it has not addressed the reliability of the absolute estimates or the influence of our Scenario. This second report conducts sensitivity analysis and compares TREES estimates with previous studies and statistics. Results show that increases in floor area and improvements in insulation significantly impact energy demand, particularly in heating-dominated regions such as Europe. Comparisons with previous studies revealed discrepancies in heating and cooling demands due to floor area and insulation settings. Statistical comparisons showed trends based on region and GDP per capita, with some countries deviating, suggesting other factors.
Key words : Global Warming, Global Energy Demand, Bottom-up Simulation, Decent Living Standard

１．緒論

筆者らは，従来は日本全国を対象として活用されてきたボトムアップ型のエネルギー最終需要推計モデルである TREES（Total Residential End-use Energy Simulation）の推計対象を世界各国に拡張する開発を行い，このモデルを「日本におけるトップ相当の高効率機器を用いて全世界人口の DLS（Decent Living Standard）を満たす」という想定の「DLS+HighTech シナリオ」に基づいて運用することで，世界の人々が「well-being」な生活を営むために最低限必要なエネルギー需要を推計した．その具体的な背景や内容については第 1 報 [1]に記されているため割愛する．

第 1 報では TREES の推計結果について，主に気象データと関連させながら各国の推計値を比較することで各国間の相対的なエネルギー需要の大きさに妥当性があることが示された．しかしエネルギー需要の推計値の大きさそのものに対する信頼性や妥当性については言及されていない．また設定した「DLS+HighTech シナリオ」が推計値に与えている影響についても十分に議論がなされていない．特に暖冷房需要は家庭部門エネルギー需要の中でも大部分を占める重要な要素であり，その大きさに影響を及ぼす因子や影響の度合いを特定することは具体的な省エネルギー施策を検討するうえで不可欠である．

したがって第 2 報では，エネルギー需要推計の対象とする住宅の床面積，断熱性能といった計算条件設定についての感度解析，および既往研究や統計値との比較について取り扱う．各々の条件設定が推計値に及ぼす影響を定量的に評価することで各々の設定がエネルギー需要の削減にどの程度有効であるかを把握し，既往研究および統計値との差やその要因について議論することで，TREES による推計の妥当性を検討することを第 2 報の目的とする．

*大阪大学大学院工学研究科環境エネルギー工学専攻
〒565-0871 大阪府吹田市山田丘 2-1-M3 棟 3 階
E-mail：gomi@ue.see.eng.osaka-u.ac.jp

２．手法

2.1 計算条件設定の感度解析

本研究で感度解析の対象とする計算条件設定は，一人当たり床面積と断熱性能である．これらについて，以下の**表 1** に示すように設定を変え，それぞれの場合のエネルギー需要を推計し比較することで，感度解析を行った．

表 1 について，シナリオ①は第 1 報における計算条件と同じものであり，一人当たり床面積は Kikstra et al.の研究 [2]において DLS の基準とされる値に従うものである．シナリオ②の一人当たり床面積は，同じく Kikstra et al.の研究にお

いて使用された西洋諸国向けの基準とされる値に従う．

表 1　各計算条件の設定

番号	一人当たり床面積	断熱性能
①	1 人あたり最低 10 m^2，ただし 3 人世帯までは最低 30 m^2	各国で最適 な断熱性能
②	1 人世帯：最低 37 m^2 2 人世帯：最低 50 m^2 3 人以上：1 人あたり最低 20 m^2	①と同じ
③	①と同じ	無断熱
④	①と同じ	ZEH 基準

なお, TREES で設定可能な住宅類型と延床面積は**表 2** に示すように戸建住宅と集合住宅でそれぞれ 6 段階であるため，本研究では**表 1** の条件を満たすもののうち最小の床面積をもつ住宅類型を採用した．またシナリオ③，④については，TREES で考慮可能な全 5 段階の断熱性能のうち最低レベルである無断熱と最高レベルである ZEH 基準断熱を使用している．

表 2　TREES で設定可能な住宅類型とその延床面積

住宅類型	延床面積 [m^2]
戸建 1	35.60
戸建 2	50.51
戸建 3	66.26
戸建 4	88.61
戸建 5	104.35
戸建 6	123.40
集合 1	19.87
集合 2	33.12
集合 3	49.68
集合 4	67.08
集合 5	84.47
集合 6	101.03

2.2 既往研究との比較

本研究と類似する条件設定の推計の研究として Grubler et al.[3]の LED（Low Energy Demand）シナリオについての研究がある．当該研究では 2050 年における一人当たりの家庭部門エネルギー需要を Global North と Global South のそれぞれで用途別（冷蔵庫，テレビ，照明，調理，熱サービス）に算出している．本研究では各国の用途別エネルギー需要推計値を LED シナリオのエネルギー需要推計値と比較する．

2.3 統計値との比較

各国の家庭部門エネルギー需要の統計値として IEA による World Energy Balances[4]を使用し，本研究の推計値と比較する．この比較により，本研究で設定した DLS+HighTech シナリオに従った場合にエネルギー需要をどの程度削減できるかを評価することができる．なお，統計値として用いる値は 2021 年のものである．

3．結果

3.1 計算条件設定の感度解析

(1) 床面積

シナリオ①とシナリオ②の暖冷房需要の比較を**図 1** に示す．なお，図中の破線は各地域のプロットに基づく回帰直線である．

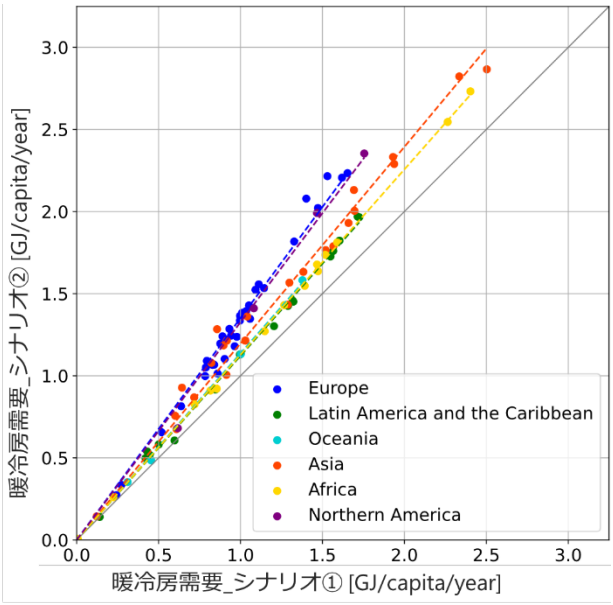


図 1　シナリオ①とシナリオ②の暖冷房需要比較
（地域によって色分け）

図 1 について，いずれの国でも床面積の拡大がエネルギー需要を増大させることがわかる．増大の程度には地域差がみられ，最も程度が大きいのはヨーロッパ（Europe）および北米（Northern America）で約 8%～約 49%，次いでアジア（Asia），オセアニア（Oceania），アフリカ（Africa），中南米（Latin America and the Caribbean）の順にエネルギー需要増大の程度が大きい．

図 1 と同じデータを，各国の暖冷房の使われ方によって色分けしてプロットした散布図を**図 2** に示す．暖冷房需要全体のうち，冷房需要の割合が大きい国は水色が，暖房需要の割合が大きい国は橙色が濃く表示されている．

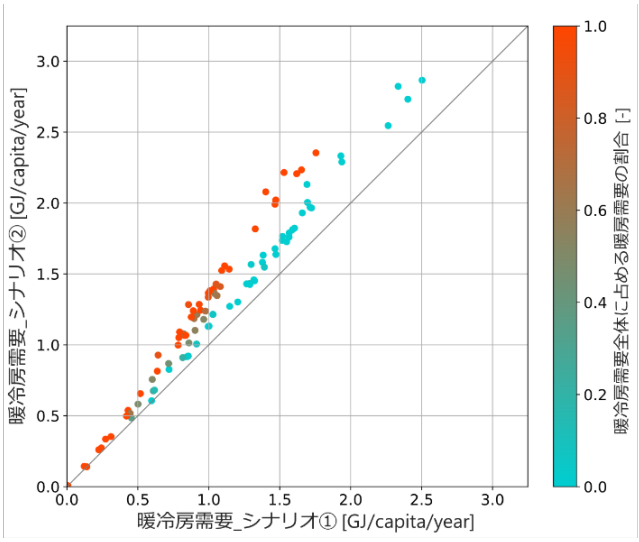


図 2　シナリオ①とシナリオ②の暖冷房需要比較
（暖房・冷房の傾向によって色分け）

図 2 から，暖房を主に使う国における増大率が冷房を主に使う国における増大率よりも大きい傾向にあることがわかる．また，一人当たりの暖冷房需要が年間 1.75 GJ を超えるのは冷房を主に使う国のみであることがわかる．

(2) 断熱性能

無断熱であるシナリオ③および ZEH 基準断熱のシナリオ④の，各国の暖冷房需要を**図 3** に示す．なお，ヨーロッパの回帰直線と北米の回帰直線が重なって見えていることに注意されたい．**図 3** について，住宅の断熱性能を無断熱から ZEH 基準に替えた場合の暖冷房需要削減の効果は，北米やヨーロッパで大きく，アフリカでは小さい傾向にあることがわかる．北米やヨーロッパにおける各国の削減率は約 53%～77%であるのに対し，アフリカにおける各国の削減率は約 15%～75%（後述するエチオピアを除けば約 15%～62%）である．またアジアや中南米はどちらともいえない国が多いことが読み取れる．

一方，**図 3** 中に大きく示した 4 か国のようにこの傾向から外れた国も存在する．例えばエチオピア（ETH_AA）はアフリカの国であるが，断熱性能の向上による暖冷房需要削減の効果が約 75%と大きい．キルギス（KGZ_GB）やカザフスタン（KAZ_ALM）についても，アジア全体の傾向に比べて需要削減の効果が大きく，それぞれの削減率は約 79%と約 80%である．また反対に，インド（IND_MH）の需要削減の効果はアジア全体の傾向に比べて小さく，削減率は約 32%である．

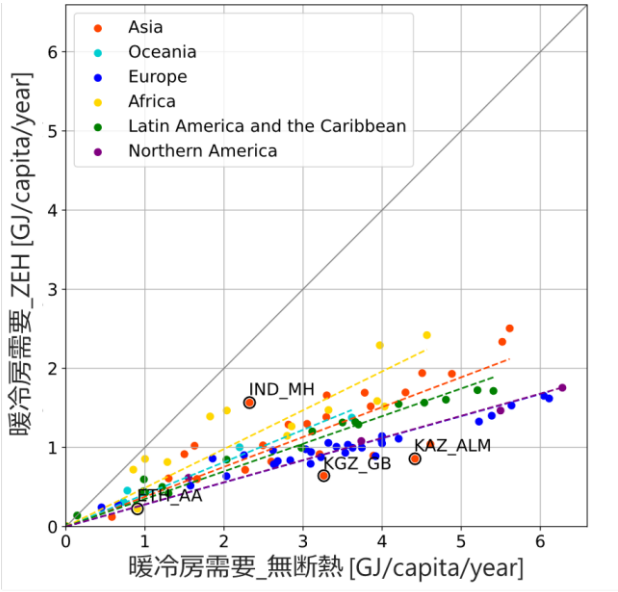


図 3　断熱性能ごとの暖冷房需要の比較
（地域によって色分け）

図 4 には，**図 3** と同じデータを各国における暖冷房の使われ方によって色分けしてプロットした散布図を示す．**図 4** から，暖房需要が主な国では断熱性能の向上による暖冷房需要削減の効果が大きく，冷房需要が主な国では効果が小さいことがわかる．また，**図 3** では各地域の傾向から外れていた 4 か国も，**図 4** における暖冷房の使い方による傾向には当てはまっていることがわかる．

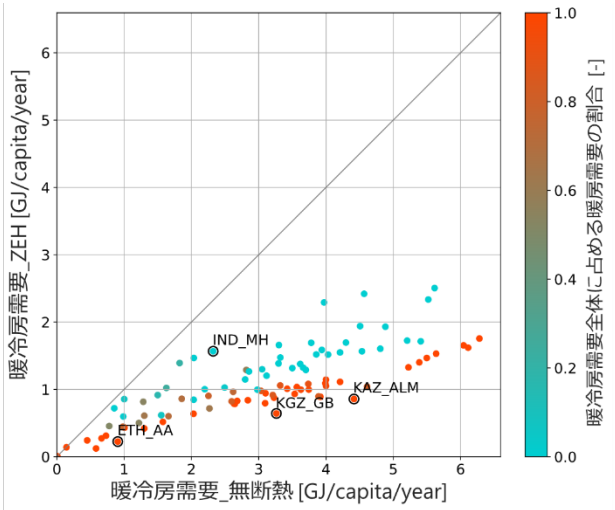


図 4　断熱性能ごとの暖冷房需要の比較
（暖房・冷房の傾向によって色分け）

3.2 既往研究との比較

LED シナリオとの比較を**図 5**～**図 7** に示す．ただし LED シナリオに合わせて用途別にエネルギー需要を示している．

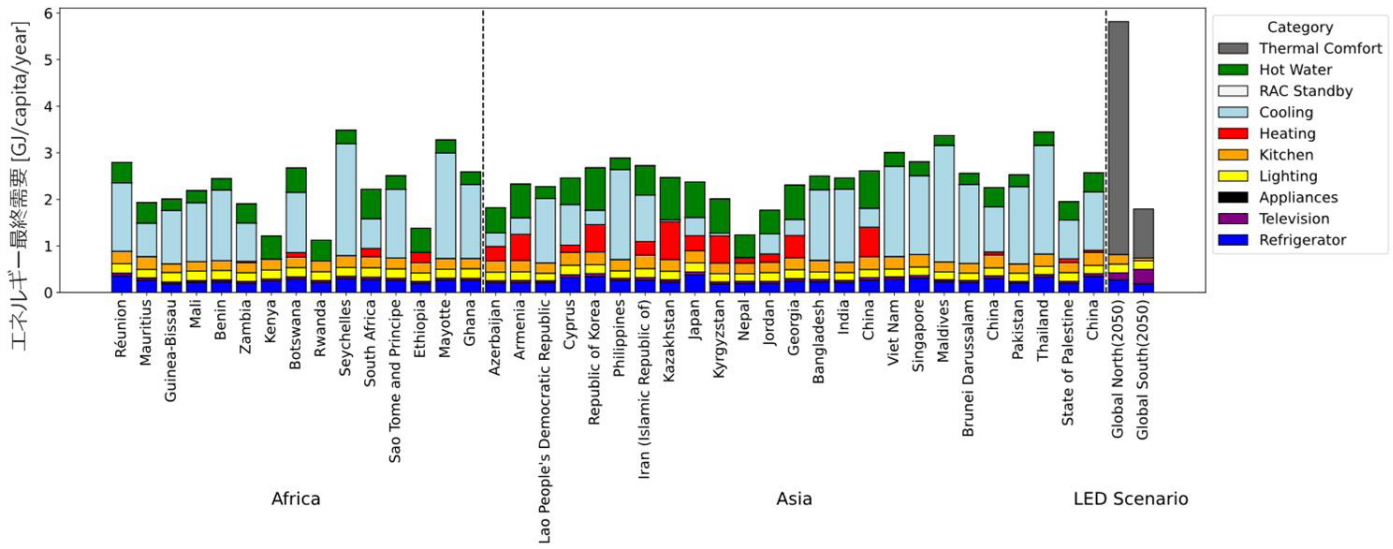


図 5　LED シナリオとの比較（アフリカ，アジア）

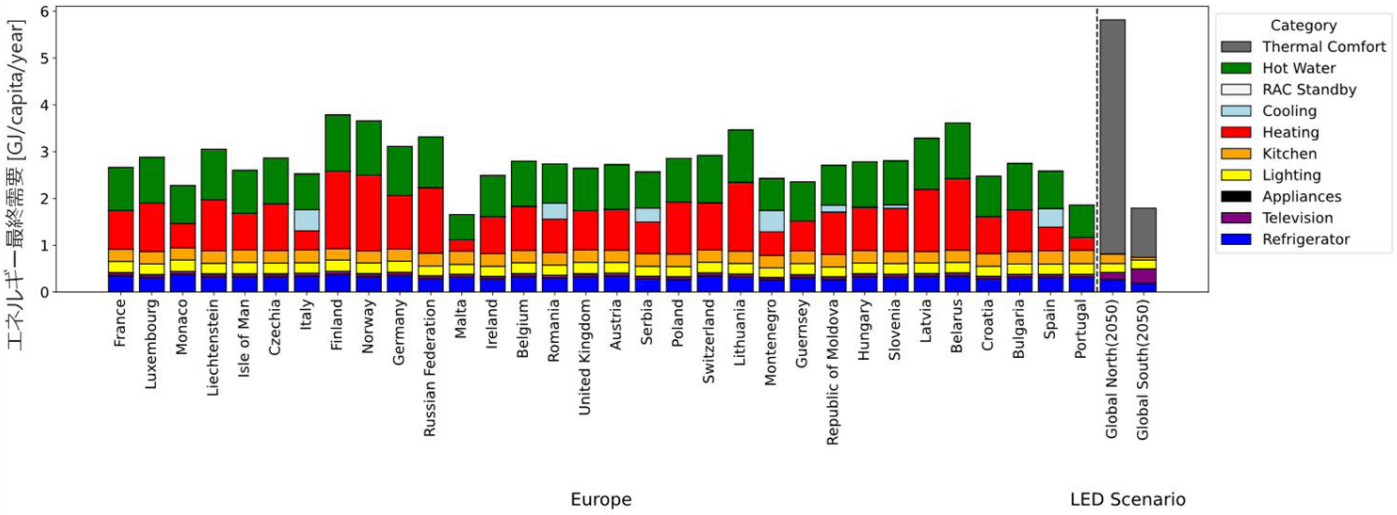


図 6　LED シナリオとの比較（ヨーロッパ）

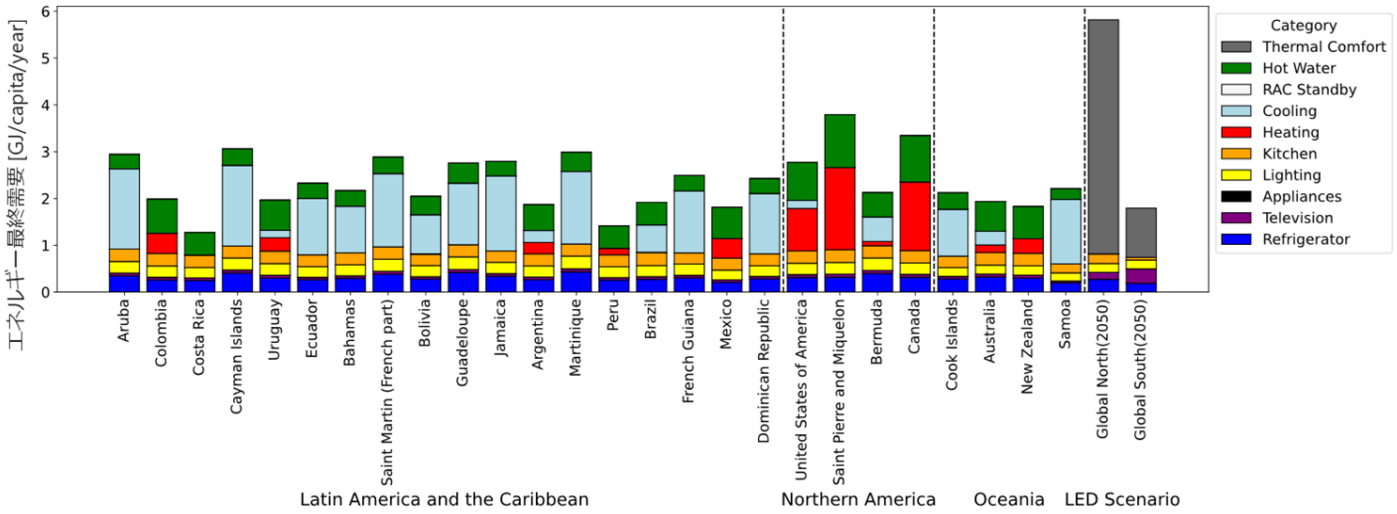


図 7　LED シナリオとの比較（中南米，北米，オセアニア）

図 5～**図 7** について，冷蔵庫（Fridge），照明（Lighting），調理（Cooking）に関するエネルギー需要の大きさは，TREES と LED シナリオで概ね一致している．テレビ（TV）については TREES の方が小さいことがわかる．また暖冷房（Heating，Cooling）および給湯需要（Hot Water）の合計値は Global North においては LED シナリオよりも小さく，Global South においては国によって大小関係が異なる．

3.3 統計値との比較

World Energy Balances の統計値との比較を**図 8** に示す．

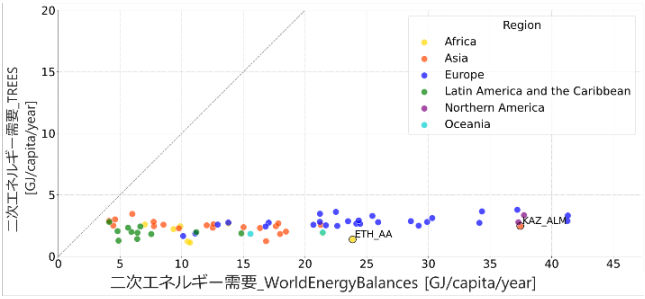


図 8 TREES の推計値と World Energy Balances の統計値の比較

図 8 について，いずれの国においても TREES の推計値は World Energy Balances の統計値に比べて小さく，その比は約 0.07～0.75 であった．**図 8** から中南米，アフリカ，アジアは推計値と統計値が比較的近い傾向にあることがわかる．反対に，ヨーロッパや北米の国は推計値と統計値が大きく離れている傾向にある．一方，**図 8** 中に示したエチオピア（ETH_AA）やカザフスタン（KAZ_ALM）のようにこのような傾向から外れる国も存在する．

4．考察

4.1 計算条件設定の感度解析

(1) 床面積

暖房需要を主とする国で床面積拡大による需要増加率が大きく，冷房需要を主とする国では需要増加率が小さかったことについて，いくつかの要因が考えられる．

一つは，床面積が拡大しても内部発熱は増加しないことである．一人あたりの床面積が小さい場合は内部発熱が室温に与える影響が比較的大きいが，床面積が拡大するとその影響は小さくなる．そのため，暖房時にはより多くのエネルギーを要する一方で冷房時には熱負荷が小さくなり，前述のような結果が得られたと考えられる．

(2) 断熱性能

暖房需要を主とする国で削減効果が大きく，冷房需要を主とする国で削減効果が小さかった．この要因として，暑い環境では断熱性能が向上すると住宅内部の熱が室内に篭りやすくなり，それに伴い冷房需要が増加してしまうことが考えられる．ZEH 基準の断熱性能をもつ住宅の場合，冷房時の貫流熱取得は無断熱の住宅に比べて小さいため室内が暖まりづらく，冷房に必要なエネルギーは小さくなる．その一方で，内部発熱や窓からの日射取得熱が室外に逃げることを妨げるため，室内に熱が篭り冷房に必要なエネルギーを増加させる要因にもなる．これらのはたらきが一部相殺するため，暖房需要が主な国に比べて削減効果が小さくなると考えられる．

4.2 既往研究との比較

テレビの消費量が TREES で小さかったのは，主に本研究の TREES の推計におけるテレビの保有状況設定によるものと考えられる．本研究ではテレビは世帯人数によらず 1 世帯に 1 台のみ，居間に設置しており，そのサイズは TREES で考慮可能なうち最小のものとしている．

また Global North における暖冷房需要の推計値と給湯需要の推計値の合計が LED シナリオよりも小さかった要因のひとつとして，床面積の設定値の違いがある．本研究の TREES の推計では**表 1** の①に示す床面積を設定しているが，LED シナリオにおける床面積は 1 人当たり最低 30 m^2 である．つまり LED シナリオの方が一人当たりの床面積が大きいため暖冷房需要が大きく推計されたと考えられる．

他の要因として，第 1 報に記したように，本研究の TREES の推計において各国の断熱性能が暖冷房需要を小さくするように最適化されていたことが挙げられる．最適化の結果ほとんどの国で ZEH 基準の断熱性能が採用されており，それが全ての住宅に適用されたものとして推計を行っていた．

また，機器性能の想定が異なることも要因として挙げられる．本研究の TREES の推計では給湯器として全て電気ヒートポンプ式のものを想定し，その効率も日本におけるトップ相当の高効率としていることから，給湯需要が小さく推計されたと考えられる．

4.3 統計値との比較

図 8 と同じデータを一人あたり GDP の大きさによって色分けした散布図を**図 9** に示す．**図 9** から，一人あたり GDP が大きい国では TREES の推計値と統計値の差が大きい傾向にあることが読み取れる．これは，経済的に発展した国で DLS を超えるエネルギーサービスが提供されていることを示唆する．一方，カザフスタンを含めいくつかの国はこの傾向からも外れており，経済的な豊かさ以外にも要因があると考えられる．

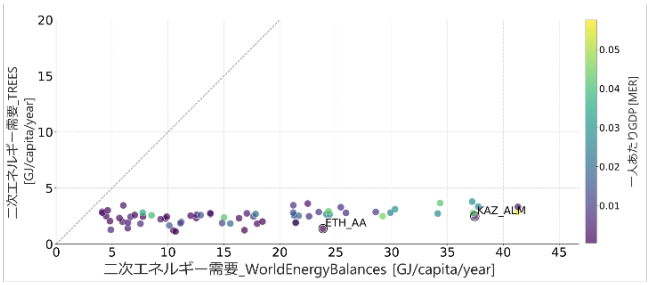


図 9　TREES の推計値と World Energy Balances の統計値の比較（一人あたり GDP で色分け）

また一人あたり GDP の小さい国でも統計値は TREES の推計値よりも大きく，あらゆる国で DLS が満たされているように見えるが，本研究の TREES の推計には第 1 報に記された通り十分なデータが得られる国のみが含まれているため，十分なデータを得られない傾向にある発展途上国についてはその多くが本推計に含まれていないことに注意が必要である．また，本推計に含まれている国でも，例えば効率の低い暖房方式が普及している国ではエネルギー需要の統計値が大きく出やすいため，必ずしも DLS 以上の水準が保証されているとはいえない．

５．まとめと今後の課題

本研究では，世界の人々が「well-being」な生活を営むために最低限必要なエネルギー需要の推計について，暖冷房需要推計に大きく影響する床面積と断熱性能の感度解析を行った．その結果，床面積や断熱性能の変化が暖冷房需要に与える影響は，暖房需要が支配的な国ほど大きく，冷房需要が支配的な国では比較的小さい傾向にあることがわかった．

また，既往研究との比較では主に暖冷房需要に推計値の乖離があることがわかり，この乖離の要因には，本研究における床面積や断熱性能の設定による影響が含まれることが示唆された．統計値との比較では，各国の位置する地域や一人あたり GDP の大きさによって統計値との近さにある程度の傾向があることが認められたが，その傾向から外れる国もあることがわかり，他の要因による影響が存在すると考えられた．

今後の課題としては，本研究で取り扱った計算条件以外の各条件，例えば暖冷房機器の稼働条件に関して感度解析を行うことや，推計対象とする国の数を増やすことなどが挙げられる．これらが達成されれば，より具体的かつ確からしい考察が期待されるとともに，世界的なカーボンニュートラル社会の実現に向けて取り組むべき施策を検討する際の省エネルギー対策の選択肢が増えることや，各国に対して最適な対策の提案が実現することが期待できる．また，統計値との比較において本研究では全ての国で推計値が統計値を下回ったが，推計対象の国を増やすことができれば統計値を上回る（統計値が DLS を満たす推計値よりも小さい）国が見つかる可能性がある．

既往研究との比較においては，分析をより詳細に行い本研究で開発したモデルの信頼性や特徴を議論するために，既往研究の条件設定に可能な限り近づけたシナリオで推計を行うことが有効であると考えられる．

謝辞

本研究は RITE および IIASA が運営する EDITS（Energy Demand changes Induced by Technological and Social innovations）プロジェクトの支援を受け実施されたものである．

参考文献

1) 石原沙莉，五味勇心，正野景大，内田英明，下田吉之; 世界の家庭部門エネルギー最終需要推計に関する研究～第 1 報　計算条件設定と推計結果について～，第 41 回エネルギーシステム・経済・環境コンファレンス, 11-1 (2024).
2) Jarmo S Kikstra, Alessio Mastrucci, Jihoon Min, Keywan Riahi and Narasimba D Rao; Decent living gaps and energy needs around the world, Environmental Research Letters, 16-9 (2021).
3) Arnulf Grubler, Charlie Wilson, Nuno Bento, Benigna Boza-Kiss, Volker Krey, David L. McCollum, Narasimha D. Rao, Keywan Riahi, Joeri Rogelj, Simon De Stercke, Jonathan Cullen, Stefan Frank, Oliver Fricko, Fei Guo, Matt Gidden, Petr Havlík, Daniel Huppmann, Gregor Kiesewetter, Peter Rafaj, Wolfgang Schoepp and Hugo Valin: A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies, Nature Energy, 3 (2018), pp.515-527.
4) IEA; World Energy Balances (2023).

JOURNAL OF BUILDING PERFORMANCE SIMULATION
https://doi.org/10.1080/19401493.2024.2421327

Taylor & Francis
Taylor & Francis Group

COMMENT

OPEN ACCESS Check for updates

The role of building performance simulations in citywide and national global warming mitigation policy

Yoshiyuki Shimoda

Division of Sustainable Energy and Environment Engineering, Graduate School of Engineering, Osaka University, Suita, Japan

ABSTRACT

Global warming is one of the most significant challenges facing the global building sector. Effective policymaking requires support through building performance simulation (BPS) because most global warming mitigation measures in the building sector focus on granular technologies and occupant behavior, which are difficult to evaluate using conventional macro-scale models. This viewpoint introduces a low energy demand scenario and its specific mitigation measures in the building sector, and discusses the difficulty of evaluating these measures using conventional integrated assessment models. In addition, the role of BPS as a support tool for global warming mitigation policymaking is proposed. Based on these discussions, required functions for BPS is suggested, the most important of which are the consideration of building stock heterogeneity, reproduction of existing faults in buildings, reproduction of changes in occupant behavior, correct simulation of electricity load curves, development of future weather data, and reproduction of electricity generation from building-integrated photovoltaics.

ARTICLE HISTORY
Received 9 July 2024
Accepted 18 October 2024

KEYWORDS
Global warming mitigation; policy support tool; low energy demand scenario; bottom-up simulation; building stock heterogeneity; energy management

Introduction

Since the adoption of the Paris Agreement in 2015, the movement toward rapid decarbonization has progressed globally. The Intergovernmental Panel on Climate Change (IPCC) presented greenhouse gas (GHG) emission pathways in the 'Global Warming of 1.5°C' special report (Intergovernmental Panel on Climate Change 2022), which states that anthropogenic CO_2 emissions should be roughly zero by 2050 to limit the temperature increase since pre-industrial levels to less than 1.5°C. The subsequent IPCC Sixth Assessment Report (AR6) (Intergovernmental Panel on Climate Change 2023) presented four illustrative mitigation emission pathways, namely 'Neg', 'Ren', 'LD', and 'SP', which correspond to the 2050 net-zero pathways that promote negative emission technologies, renewable energy, low energy demand, and sustainable development, respectively. Because global energy demand is significantly reduced in the LD and SP scenarios, the energy demand of the building sector must also be greatly reduced. To date, building performance simulation (BPS) has not contributed much to the development of these scenarios. However, there is expected to be an increase in evaluations that require BPS capable of correctly reproducing building physics, such as the rapid increase in energy demand for cooling due to the spread of air conditioning in various types of buildings in line with improvements in living standards in the Global South (International Energy Agency 2018).

While conventional BPS usually provides building designers with highly accurate planning data based on complete information, city- or nation-scale model provide policymakers with GHG reduction effects resulting from various mitigation scenarios as values with uncertainty based on incomplete information. Therefore, in addition to differences in the number of buildings covered, there are also differences in the content of the BPS. Furthermore, as the size of a target building increases, the calculation load also increases, so techniques for simplifying calculations are also required.

The aim of this Viewpoint Paper is to demonstrate that BPS can play a major role in the development of policies to accomplish the significant reduction in energy demand that the building sector must achieve in the future, and to discuss how BPS can contribute to this and what functions should be added to BPS.

Low energy demand (LED) scenario and buildings

A representative study of the drastic reduction in global energy demand is the LED scenario proposed by Grubler et al. (2018). This scenario narrative has five main drivers

CONTACT Yoshiyuki Shimoda shimoda@see.eng.osaka-u.ac.jp Division of Sustainable Energy and Environment Engineering, Graduate School of Engineering, Osaka University, 2-1, Yamadaoka, Suita, 565–0871, Japan

© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (http://creativecommons.org/licenses/by-nc-nd/4.0/), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

Table 1. Avoid–shift–improve approach for building service.

Service	Avoid	Shift	Improve
Thermal comfort	Reviewing floor space by shared use and multi-generational housing, temperature settings, dress code, and change of working hours	Passive design with shading and natural ventilation	Solar heating, enhanced insulation, heat pumps, district heating, etc.
Lighting	Room occupancy sensors and illuminance control	Maximum daylight utilization	LED lamps

Adapted from the IPCC AR6 report (Intergovernmental Panel on Climate Change 2023).

of long-term changes in energy end use: quality of life, urbanization, novel energy services, end-user roles, and information innovation. These drivers show that the transition to low energy demand occurs on a small scale, greatly impacting individuals. For example, the area of living space with thermal comfort or number of consumer devices is defined as the minimum service for residential occupants, and they are provided the minimum amount of energy to use the most advanced technologies in existence. The LED scenario was the basis for the LD scenario in the IPCC AR6 report, which proposes an avoid–shift–improve approach; that is, avoiding unnecessary services for well-being, shifting to existing competitive efficient/low-carbon service provision systems, and improving efficiency and carbon intensity. Examples of the avoid–shift–improve approach for thermal comfort and lighting services are listed in Table 1. BPS, which reproduce physical phenomena in buildings, is considered the most appropriate tool for evaluating granular technological and behavioral changes.

Buildings and global warming mitigation

As a major energy end-use sector, the building sector plays four roles in global warming mitigation:

(1) Reduce energy demand. In addition to increasing the energy efficiency of building equipment and appliances, the avoidance and shifting of services for occupants, as described above, must be considered. Owing to their long-lived nature, most existing buildings are equipped with outdated technology; therefore, a considerable reduction in energy demand can be expected by substituting it with the latest technology. To evaluate such future heating/cooling/hot water energy demand reduction, the rise in outdoor temperature must be predicted and considered.

(2) Select end-use energy. Most primary end-use energy sources in buildings are fossil fuels. Although electricity can also be generated from renewable energy sources or nuclear power, fuel mostly comes from fossil fuels. The electrification of buildings is currently seen as a secure way to transition toward decarbonization. Because the temperature of heat consumed in buildings is lower than that consumed in factories, it can be supplied by heat pumps. The use of hydrogen and biomass fuels usually requires the retrofitting of facilities. Therefore, if e-fuel is not commercialized, current fuel-combustion facilities will not be available in a carbon-neutral society. Building equipment has a long life, and if the wrong decision is made at the time of a new installation, the risk of a lock-in effect could persist for a long period. Thus, careful equipment selection is required to forecast long-term changes in energy technology.

(3) Flexibility provision to the electricity grid. An increase in variable renewable electricity sources, such as photovoltaic (PV) and wind power, destabilizes the instantaneous balance of electricity supply and demand and consequently affects grid frequency and voltage. PV power generation is concentrated in the daytime, resulting in a surplus electricity supply during the daytime and a shortage at night. This characteristic shape of the electricity load curve is called the 'duck curve'. The load on other conventional power generation facilities rises sharply in the evening and requires the rapid dispatch of thermal plants, making stable operation difficult. Furthermore, as electric vehicles become more widespread, and residential charging becomes more popular, the electricity load in the evening will increase. To avoid this effect, the conventional energy demands of buildings must be adjusted to mitigate these fluctuations. The U. S. Department of Energy proposed a new building energy system concept of the 'Grid-interactive Efficient Building' (U. S. Department of Energy 2021), which provides efficient building services using sensing of the indoor environment, while adjusting the electricity demand according to the requirements from the grid by using distributed power source such as battery and PV.

(4) Achieve synergies between mitigation and adaptation. In the future, not only will there be an outdoor temperature rise, but heavy rains, storms, and floods are also expected due to global warming. As weather disasters have significant impacts on occupants and buildings, adaptation measures are essential. For cooling, a synergy between mitigation and adaptation measures, that is, the provision of efficient and decarbonized cooling services, is strongly required.

Limitations of conventional global warming mitigation policy support tools

The Integrated Assessment Model (IAM) is widely used in the development of global warming mitigation pathways for policymaking. The IAM aims to provide policymakers with meaningful information by integrating models of the economy, energy systems, climate change mechanisms, and land use to address climate change concerns that cannot be solved by specific disciplines. In the context of the building sector, existing models that simulate energy use at local, national, and global scales were reviewed by Mastrucci et al. (2023). Notably, in addition to the problem of technological and behavioral granularity, IAMs have some deficits in building sector modeling.

First, the technology selection model in the IAM cannot accurately reflect the 'service demand–technology–end use energy demand' structure in buildings because it covers various kinds of energy use in a wide area, such as a country or the world. For example, it is difficult to precisely evaluate combined energy efficiency of wall insulation and heat pump heating because heating loads are usually exogenously given as the service demand in most IAMs. In addition, although the economic model in the IAM usually assumes that each entity makes economically rational technology choices, the household sector, which makes technology choices in residential buildings, does not always make economically optimal choices. Furthermore, heterogeneity makes the cost performance of the mitigation measures diverse, which cannot be considered by conventional IAMs. Because the effectiveness of regulatory measures should be examined, not only economically optimum solutions but also technological potential may provide important information to policymakers.

Building performance simulations for global warming mitigation policymaking

BPS can be useful in the implementation of national and urban GHG emission reduction policies by assessing the effectiveness of measures in the planning stage and quantitatively evaluating the effects of each measure during policy implementation.

Building performance simulation for long-term policymaking tool

In the building sector, the future projections of energy consumption, including energy-consuming equipment and appliances inside buildings, and long-term effects of various energy-efficiency measures must be assessed for policymaking. The power-generation potential of building-integrated PVs should also be assessed. As buildings generally have a long lifespan, measures in policymaking should not only be considered in new buildings, but also during renovations. Energy efficiency measures for buildings can be classified into a hierarchy of district-level, building-level, and equipment/appliance-level measures as well as occupant behavioral changes. As the introduction of energy-efficient equipment such as light-emitting diode lighting affects cooling/heating loads or changes the heating load owing to insulation enhancement, the load factor of heat pumps can affect their COP. Measures at each tier affect other measures, and the usefulness of BPS in evaluating these measures is significant.

Thus far, planning tools such as IAMs have used simplified calculations, such as estimating energy consumption by providing uniform efficiency and operation times for all households/buildings or estimating heating and cooling loads using the degree-day method and converting them to electricity consumption at a constant COP. BPS is expected to become a powerful bottom-up approach. In addition, the simulation of the surrounding environment, such as neighboring buildings and green spaces, needs to be combined when considering the use of solar radiation, as in the case of daylighting, passive heating, or PVs, or when considering outdoor air cooling. The challenge is in how the lifetime and replacement of building stock and equipment/appliances can be predicted, and how innovative technologies and measures that are not currently in practical use can be simulated.

Digital twin of city or nation for progress management of mitigation policy

Digital twins of cities or nations can also be used for the progress management of mitigation policies. Many cities and countries have set GHG emission reduction targets, such as those for 2030 and 2050, and are implementing policies to accomplish these targets. After the GHG reduction policy is initiated, the progress of the policy is difficult to monitor because the degree of progress of each measure, such as the dissemination of high-insulation buildings and high-efficiency equipment, is difficult to observe, and even if such dissemination can be observed, the energy reduction effect by implementing a unit of energy or GHG reduction measures varies from household to household owing to their heterogeneity (e.g. in occupant behavior). In addition, the measured energy/GHG change by top–down statistics is subject to external factors unrelated to the policy, such as weather conditions and socioeconomic activities.

Shimoda et al. (2022) proposed an 'energy and carbon management system' consisting of a bottom-up end-use simulation model, individual statistical data, and smart

meter data. The annual energy demand of the Japanese residential and non-residential sectors is simulated for 2013–2019 by this system. As a result, the impact of differences in weather conditions from base year was segregated and net effect of each measure was evaluated quantitatively.

Requirements for building performance simulation as a policymaking tool

To ensure compatibility with the above applications, the following functions should be included in BPS.

Reproduction of household and building heterogeneity

One of the most important requirements for reproducing building sector energy consumption at the urban and national scales is the reproduction of the heterogeneity of building stock. For residential buildings, the household member composition, occupant behavior, house classification (e.g. detached or multi-family), house size, equipment/appliance type, number, and capacity, equipment/appliance energy performance (production year), and building insulation level varies from household to household. For non-residential buildings, building use, building size, equipment specifications, building and equipment energy efficiency, and hours of operation also vary. Because energy consumption and the effect and marginal cost of mitigation measures are significantly affected by these elements, reproducing these heterogeneities is a key concern in modeling the energy use of the building sector at urban and national scales.

An important aspect of meeting this requirement is the correlation between the parameters. For example, the width of the house, number of household members, and number of appliances are correlated, which leads to a greater difference in energy consumption between households than if each parameter is independent. Matoba et al. (2020) succeeded in reproducing up to a four-fold difference in household energy consumption under the same weather conditions in a four-person household, considering other parameters such as differences in building energy efficiency and appliance ownership. Traditionally, all building stocks are classified into a small number of categories considering these correlations, and the total energy consumption is estimated by summing the simulated energy consumption of representative buildings for each category. In recent years, progress in computing capacity has made it possible to generate random combinations of parameters while considering the correlations. Urban- and national-scale energy consumption can be derived from the results of a large number of calculations. At the city-scale, performing building-by-building simulations may be possible. The United States has a database of information on the location and type, size, shape, etc. of 123 million buildings in the country that can be used as input for building energy simulations (New et al. 2021). A method for estimating the regional energy consumption should be developed using as few simulations as possible while preserving the heterogeneity of the original population. On a national scale, variations in weather conditions may also be a problem, and in cities, the effects of microclimatic conditions may need to be considered.

Reproduction of faults in the energy use procedure

BPS usually simulates buildings that are designed, constructed, and operated properly. However, few buildings follow such models, and most buildings in the real world have various faults, as follows:

(a) Problems at the design and construction stage, such as overcapacity of equipment.
(b) Decrease in efficiency due to age-related deterioration of buildings and equipment.
(c) Reduced efficiency due to excessive service demands by occupants, such as leaving lights on and setting excessive room temperatures.
(d) Energy loss due to securing capacity allowance in equipment operation.

Owing to these factors, the simulation results for countries and cities are generally lower than the energy consumption reported in the energy statistics. In addition, the role of home energy management system (HEMS) and building energy management system (BEMS) is to correct such faults (i.e. c and d). However, because these faults have not been quantified, the energy-saving potential of these energy management systems is difficult to assess. Replicating realistic building stock energy consumption, including such faults, is another major challenge when BPS is used as policy assessment tools.

Replication of occupant behavior

An evaluation tool for future global warming mitigation policies must be able to replicate the avoidance of excessive services for occupants, as well as significant time-use schedule changes, such as teleworking and e-commerce. To determine the operation hours of equipment and appliances, which are important factors in determining the energy consumption of each appliance, more accurate modeling of occupants' time-use schedule behavior is required.

Reproduction of electricity load curves

An accurate representation of electricity load curves on a city-by-city or district-by-district basis is necessary to evaluate the flexibility of electricity demand for buildings and building stock and assess the impact of the spread of solar power generation on electricity grids. For this purpose, heterogeneity in lifestyle behaviors is important. For example, a schedule in which everyone in a city simultaneously performs the same activity at the same time will result in unrealistic electricity load curves. The factor that causes the electricity load curve to vary significantly is the power consumption of heating and cooling; therefore, an accurate reproduction of the load curve requires suitable weather data. The degree-day and variable-degree-day methods (Al-Homoud 2001) normally used in IAMs cannot reproduce load curves. To evaluate thermal storage in building walls and floors, the heat transfer in these parts must be modeled correctly. The time-series changes in heating/cooling load and PV generation driven by weather conditions and in appliance/equipment power consumption driven by occupant must be realistically reproduced. Smart meters are effective tools for evaluating and calibrating simulated load curves. Simulation of a future with widespread electric vehicle requires modeling the amount and schedule of charging from buildings to electric vehicles. The charging schedule for electric vehicles is determined by the vehicle's operating schedule, which must be consistent with the building occupants' behavior schedule. Integration with simulation of the entire power system or power distribution system and standardization of requirements such as time and spatial resolution for such integration will become important. These simulations will also require modeling of load curve adjustment by storage batteries, V2H, etc.

Provision of weather data for building performance simulations based on future climate change prediction

The changes in cooling and heating loads, efficiency of HVAC systems, and amount of solar radiation due to climate change can significantly impact the results of building energy and water consumption simulations. Methods are therefore required to convert the global-scale results of various climate change scenarios into weather data with high temporal and spatial resolution for the input data of BPS.

Calculation of building-integrated PV power-generation potential considering building geometry

As PV power generation varies over time depending on solar radiation, the amount of power generated from the orientation and area of the roof and walls must be calculated. The time-of-day pattern of power generation varies depending on the orientation of the panels. It can also be used for energy management by overlapping the electricity load curve consumed by the building.

In order to steadily respond to the abovementioned requirements, the increase in computational time becomes a problem. Originally, the use of BPS for the national housing and building stock generates an extremely large computational load. The minimum requirement that the simulations discussed in this paper must meet is not the accuracy of the calculation of energy consumption of individual buildings, but the accuracy of the energy consumption and its change in the entire building stock. Therefore, it will be necessary to develop a statistical method that can reflect the heterogeneity within the stock and occupant behavior with a minimum computational load while ensuring the accuracy of the entire stock. On the other hand, there may be an opinion that for the important problem of global warming mitigation, it is also necessary to develop a large-scale model that preserves as much as possible the characteristics of the simulation target, in the expectation of increased computational capacity.

In addition, the calculations may become too complex, making it difficult to understand the implications for policymaking. There is a need to discuss the balance between consideration of heterogeneity in the building sector and policy clarity. Consideration should also be given to accurately calculating the cost of the measures.

Conclusion

In this viewpoint, the role of BPS in global warming mitigation policies was discussed. BPS plays a significant role in identifying the role of the building sector in the achievement of a decarbonized society. As building energy consumption is significantly affected by weather conditions, different measures must be taken in different regions. In addition, to achieve ambitious targets such as the 1.5°C scenario, all possible measures that can be taken must be implemented and their integrated effects must be assessed. The key conclusions of this viewpoint are:

- To significantly reduce the energy consumption of buildings, strategies are required to identify the building services that occupants should be provided with and implement them with minimum energy consumption.
- BPS, rather than traditional IAMs, can be a useful tool for evaluating such strategies.
- Future challenges for BPS includes reproducing heterogeneity, modeling faults in energy use procedures,

modeling occupant behavior, reproducing electricity load curves, providing weather data in the future, and calculating the power generation potential of building-integrated PVs.

The building sector has a significant responsibility to achieve a decarbonized society. The author sincerely hopes that BPS will be used effectively to support building sector decision-makers in making better policies, and that enhanced simulation technologies will be developed to achieve this purpose.

Acknowledgements

The author would like to thank Professor Ian Beausoleil-Morrison for his encouragement in writing this paper and valuable comments.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Energy Demand Changes Induced by Technological and Social Innovations (EDITS) project, which is an initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and the International Institute for Applied Systems Analysis (IIASA), and funded by the Ministry of Economy, Trade, and Industry (METI), Japan; JSPS KAKENHI Grant Number JP23K26261.

Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

References

Al-Homoud, M. S. 2001. "Computer-aided Building Energy Analysis Techniques." *Building and Environment* 36:423–433. https://doi.org/10.1016/S0360-1323(00)00026-3.

Grubler, Arnulf, Charlie Wilson, Nuno Bento, Benigna Boza-Kiss, Volker Krey, David L. McCollum, Narasimha D. Rao, 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* 3:515–527. https://doi.org/10.1038/s41560-018-0172-6.

Intergovernmental Panel on Climate Change. 2022. *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above pre-Industrial Levels and Related Global Greenhouse gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. 616, edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, et al. Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/9781009157940.

Intergovernmental Panel on Climate Change. 2023. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, et al. Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/9781009157926.

International Energy Agency. 2018. "The Future of Cooling: Opportunities for Energy- Efficient Air Conditioning." 88 pp. https://www.iea.org/reports/the-future-of-cooling.

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): 761–792. https://doi.org/10.1146/annurev-environ-112321-102921.

Matoba, Haruka, Minami Sugiyama, Ayako Matsuoka, Yoshiyuki Shimoda, and Yohei Yamaguchi. 2020. "Analysis on Differences of Energy Consumption among Households by Simulation and Statistics." *Journal of Japan Society of Energy and Resources* 41:209–218. (In Japanese). https://doi.org/10.24778/jjser.41.5_209.

New, Joshua R., Mark Adams, Brett Bass, Anne Berres, and Nicholas Clinton. 2021. "Model America - Data and Models of Every U.S. Building. [Data Set], April 14" *Constellation*. https://doi.org/10.13139/ORNLNCCS/1774134.

Shimoda, Yoshiyuki, Misaki Fujiwara, Toshiki Nakanishi, Yohei Yamaguchi, and Hideaki Uchida. 2022. "Energy and Carbon Management System for a City and a Nation." *Proceedings of eceee 2022 Summer Study*, 501–510. Hyêres, France.

U. S. Department of Energy. 2021. "Office of Energy Efficiency and Renewable Energy, Building Technology Office." A National Roadmap for Grid-Interactive Efficient Buildings, 150 p. https://gebroadmap.lbl.gov/.