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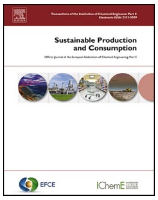

(In)Sufficiency of industrial decarbonization to reduce household carbon footprints to 1.5°C-compatible levels

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ABSTRACT

Scenarios that limit global warming to 1.5°C rely on a combination of interventions to reduce greenhouse gas emissions and capture carbon dioxide. However, the extent to which lifestyle change contributes to mitigation relative to technological change over time remains understudied. Here, we present a scenario model that incorporates extensive supply-side technological transformations while excluding lifestyle changes. By adapting a global supply-use table from EXIOBASE using elements from Shared Socioeconomic Pathway 1 and a mitigation pathway consistent with the 1.5°C target, we assess how household footprints evolve in 2030 and 2050 and the extent to which technological change alone can mitigate greenhouse gas emissions. We modeled footprints for 49 countries/regions, with a focus on the EU27. Our scenario results indicate that while technological change can substantially reduce emissions, the reductions are ultimately insufficient to achieve the 1.5°C target. Eight EXIOBASE regions, including three EU27 countries, are on a 1.5°C-consistent trajectory with just technological advancements in 2030. However, by 2050, no countries are projected to meet the 1.5°C-compatible target. The average EU27 overshoot for household footprints approaches 2.2 tCO_2e/cap in 2030 and 3.1 tCO_2e/cap in 2050. Global overshoots are more moderate at 0.3 tCO_2e/cap in 2030 and 2.0 tCO_2e/cap in 2050. Our results highlight the critical role of household lifestyle transformation in climate change mitigation. Future research can explore the diverse lifestyle change pathways necessary to align with the aspirational 1.5°C target outlined in the Paris Agreement.

1. Introduction

Considerable reductions in greenhouse gas emissions are needed to restrict global warming to the range of 1.5°C to well below 2°C, as defined in the Paris Agreement. However, current emissions pledges are unlikely to limit warming to 1.5°C (IPCC, 2022). Risks of triggering climate tipping elements and climate-induced disasters exist even within the 1.5–2°C range (Armstrong McKay et al., 2022; Hoegh-Guldberg et al., 2019; Wunderling et al., 2023). The Sustainable Development Goals are also more likely to be met with 1.5°C of warming than with 2°C (Roy et al., 2018).

The imperative to keep global temperature rise below 1.5°C has been reflected in the increasing focus on demand-side mitigation of climate change. A milestone chapter in the Intergovernmental Panel on Climate Change (IPCC) AR6 WGIII highlighted the crucial role of lifestyle change in mitigating climate change (Creutzig et al., 2022). IPCC mitigation scenarios developed using Integrated Assessment Models (IAMs) were not designed to evaluate the contributions of lifestyle change to climate change mitigation, although the models may include elements of behavior change. An IAM may model lifestyle changes towards sufficiency, the uptake of new technologies, or other sustainable behavioral interventions as part of a sector-wide shift assuming rational choice as a response to carbon taxes (van den Berg et al., 2019). This causes difficulty in distinguishing a sector's supply-side changes from households' concerted sustainable lifestyle changes (van Sluisveld et al., 2016). Even when demand-side changes are explicitly included in IAM scenarios, the scenarios focus on how lifestyle change can reduce the dependence on technological change or negative emissions technologies rather than the absolute contribution of these changes (Bertram et al., 2018; Grubler et al., 2018; van Vuuren et al., 2018). As a result, no scenario precisely assesses the comparative contribution of lifestyle and supply-side changes to meeting the 1.5°C target.

Understanding the necessary contributions of demand-side actions also requires understanding how economic growth and technological

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change influence consumption patterns and the resulting footprints. The influence of increasing or maintaining wealth levels in high-income countries together with technological shifts has not yet been considered. This is especially interesting for countries within the European Union (EU), as these high-income countries aim for a substantial emissions reduction by 2050 (European Commission, 2021). Carbon footprints vary significantly across the EU (Ivanova et al., 2017; Ivanova and Wood, 2020), and the persistence of this pattern will lead to heterogeneous mitigation burdens. Increases in overall affluence have been shown to increase emissions in the EU (Wood et al., 2020). Changing household consumption preferences resulting from an increase in GDP per capita, such as a shift from additional marginal spending on food to transportation, will have a negligible impact on the EU's carbon footprint by 2030 (Bjelle et al., 2021). However, it is currently unclear whether future emission reductions from technological change, enabled by a more prosperous and productive society, can offset the emissions normally associated with such an affluent society.

Scenarios can offer valuable insight into the consequences of socioeconomic or technological development or evolution in consumption-based emissions in various regions. Input-output models are uniquely suited to assess footprints of consumption (Hertwich and Peters, 2009). Translating exogenous scenario specifications to an input-output or supply-and-use framework to facilitate prospective analysis is limited to a few examples (Budzinski et al., 2023; de Koning et al., 2016; Duchin and Lange, 1994; Wiebe et al., 2018). These studies explore emissions reduction from technological change but do not focus on the potential impact of lifestyle change.

In this paper, we present an exploratory global 'Decarbonization Divergence' sustainability scenario. This scenario depicts an economy that decarbonizes through technological development despite further growth, while households do not contribute to such decarbonization efforts through lifestyle change, leading to divergent developments between the economy and households. We construct this scenario model as a multi-regional input-output model to assess the consumption-based impacts of households. From this scenario model, we assess the extent to which EU27 and global household carbon footprints may be compatible with the aspirational 1.5°C target from the Paris Agreement and explore the effects of technological transformation on greenhouse gas emissions.

2. Methods

2.1. Scenario design

2.1.1. Theoretical background

Input-output scenarios derived from IAM-constructed elements have proven valuable in evaluating a more sustainable counterfactual compared to a baseline model (de Koning et al., 2016; Wiebe et al., 2019). Similar to earlier work, our objective was to represent the key attributes of a global economic and energy system consistent with a 1.5°C-compatible mitigation pathway within a global environmentally extended supply-use table (SUT) framework and an input-output (IO) model. However, our study takes an opposite approach to previous studies and develops a scenario that specifically isolates the effects of a lack of lifestyle change.

The SUT framework provides a detailed description of the structure of the economy from data compiled following the System of National Accounts. It consists of a supply table, representing the number of goods and services supplied to the economy, and a use table, representing the intermediate and final use of goods and services in an economy and value-added elements (Eurostat, 2008). The activities and emissions represented in a supply-use framework correspond to the production-based emissions of an economy and align with the emissions accounting of an IAM.

Technological change is primarily modeled in the SUT by changing final demand, the environmental coefficient matrices, and the intermediate product use in relevant industries. The latter also involves proportional changes to the supply of products to an economy. Changes to industry intermediate supply and use are eventually reflected in the input-output table coefficients used for calculating demand-driven carbon footprints.

Modeling technological changes in a SUT has several advantages. The number of product groups and industry sectors distinguished in a SUT often exceeds that of an IAM. A SUT provides a higher level of detail about the production of goods and services and their intermediate and final uses than an input-output table (IOT). This higher resolution allows better matching of physical to monetary units for modeling changes within sectors, such as changes to fuel types. Implementing technological changes in a SUT and balancing the system before converting the SUT to an IO model helps ensure a consistent economic system as the basis for further footprint analysis.

2.1.2. Decarbonization divergence scenario narrative

This study explores the potential emissions overshoots arising from a scenario with industrial decarbonization but no household decarbonization: a 'Decarbonization Divergence' scenario. We designed the Decarbonization Divergence scenario from an existing IPCC scenario compatible with a 1.5°C target.

The scenario-based projections used by the IPCC for assessing potential climate change impacts and mitigation are based on the Shared Socioeconomic Pathways (SSPs) and their corresponding baseline and mitigation interpretations (Riahi et al., 2017). Representative Concentration Pathway 1.9 (RCP1.9) is an emission trajectory that has the highest probability of limiting global warming to 1.5°C by limiting radiative forcing to 1.9 $\mathrm{W\,m^{-2}}$ by 2100 (Rogelj et al., 2018). Only three SSPs – SSP1 (Sustainability), SSP2 (Middle of the Road), and SSP5 (Fossil-fueled Development) – were found to be compatible with RCP1.9 by any IAM (Rogelj et al., 2018). The SSP1 scenario represents more equitable sustainable development and includes economic growth from global technological convergence (Riahi et al., 2017). SSP1-RCP1.9 is characterized by global sustainability progress, enabled by low population and high economic growth, rather than SSP2-RCP1.9's moderate population and economic growth and high carbon price (O'Neill et al., 2017; van Vuuren et al., 2017). Aside from the IPCC scenarios, few scenarios are focused on limiting warming to 1.5°C. The most ambitious scenarios compatible with 1.5°C, such as Low Energy Demand (Grubler et al., 2018) or Decent Living with Minimum Energy (Millward-Hopkins et al., 2020), explicitly incorporate dedicated lifestyle changes. The International Energy Agency (IEA) produced the Net Zero Emissions by 2050 Scenario, but this scenario mostly focuses on the energy system. Thus, SSP1-RCP1.9 offers the most suitable baseline assumptions for exploring extensive technological development without household lifestyle changes in the Decarbonization Divergence scenario.

One distinguishing aspect of this scenario is that no explicit household lifestyle changes were included. We adopted the definition of lifestyle change from van den Berg et al. (2019): behavioral changes that lead to a change in energy demand and that can be classified under the 'Avoid-Shift-Improve' framework of Creutzig et al. (2018). We refer to the baseline SSP1-RCP1.9 parameters as the 'background system' for society, as an individual would have little control over how these elements might impact their carbon footprint. A change in the energy mix or spending patterns from more income would be considered a background system change rather than a lifestyle change. As diverse behavioral responses may arise from policy interventions, we intentionally excluded any potential lifestyle changes resulting from legislation, such as the replacement of internal combustion engine vehicles with electric vehicles stimulated by an EU-wide ban.

2.1.3. Scenario specifications and data

We identified 12 distinct background system changes to model in our Decarbonization Divergence scenario (Table 1). We selected SSP1-RCP1.9 scenario data from IMAGE, the reference IAM for SSP1 (van

Table 1
Elements from SSP1 and mitigation pathways translated into modeling steps. Modeling steps refer to discrete adjustments to supply-use tables (SUTs) and input-output tables (IOTs) in the scenario model. Value change refers to the global (average) values, but national- and regional-level data were used.

Order	Application	Modeling step	Geographical resolution	Transformation/ Processing	Value change	Reference
1	SUT	Population	194 countries	Aggregate to EXIOBASE resolution	2015: 7.38E+09 2050: 8.26E+09	KC and Lutz (2017)
2	SUT	Total Factor Productivity (TFP)	33 regions (TFP)	Map and/or aggregate to EXIOBASE resolution	2015: 0.038 2050: 0.054	Leimbach et al. (2017)
3	SUT	Gross Domestic Product (GDP) and economic sector shift	184 countries (GDP) 26 IMAGE regions (sector shift)	Map EXIOBASE sectors to one of the three major sectors; map and/or aggregate regions to EXIOBASE resolution	2015: 1.15E+04 US$2005/ year/cap 6% Agriculture 32% Industry 63% Services 2050: 3.02E+04 US$2005/ year/cap 3% Agriculture 25% Industry 72% Services	GDP: Dellink et al. (2017) Economic sector composition: IMAGE 3.2, RCP 1.9: van Vuuren et al. (2017)
4	SUT	Space heating	26 IMAGE regions	Map EXIOBASE sectors; map and/or aggregate regions to EXIOBASE resolution; fuel conversion	36% CO_2 emissions reduction from 2015 for all except household sector	IMAGE 3.2, RCP 1.9, CMIP6: Gidden et al. (2019)
5	SUT	Industry	26 IMAGE regions	Map EXIOBASE sectors; map and/or aggregate regions to EXIOBASE resolution	88% CO_2 emissions reduction from 2015 levels in 2050	IMAGE 3.2, RCP 1.9, CMIP6: Gidden et al. (2019)
6	SUT	Ground transportation	26 IMAGE regions	Map EXIOBASE sectors; map and/or aggregate regions to EXIOBASE resolution; Fuel conversion	92% CO_2 emissions reduction from 2015 levels in 2050 for all except household sector	IMAGE 3.2, RCP 1.9, CMIP6: Gidden et al. (2019)
7	SUT	Maritime transportation	Global	Map EXIOBASE sectors; Fuel conversion	65% CO_2 emissions reduction from 2015 levels in 2050	IMAGE 3.2, RCP 1.9, CMIP6: Gidden et al. (2019)
8	SUT	Aviation	Global	Map EXIOBASE sectors; Fuel conversion	70% CO_2 emissions reduction from 2015 levels in 2050	IMAGE 3.2, RCP 1.9, CMIP6: Gidden et al. (2019)
9	SUT	Carbon capture and storage (CCS) in electricity systems and industrial sectors	26 IMAGE regions	Map EXIOBASE sectors; map and/or aggregate regions to EXIOBASE resolution.	2015: 0% fossil fuel CCS 2050: 80% fossil fuel CCS	IMAGE 3.2, RCP 1.9: van Vuuren et al. (2017)
10	SUT	Electricity mix	26 IMAGE regions	Downscale to EXIOBASE country resolution	2015: 8.69E+10 GJ (23% renewable) 2050: 1.78E+11 GJ (63% renewable)	IMAGE 3.2, RCP 1.9: van Vuuren et al. (2017)
11	SUT	CH_4 and N_2O mitigation (agriculture, waste, energy)	14 regions (agriculture) 26 IMAGE regions (waste, energy)	Map EXIOBASE sectors; map and/or aggregate regions to EXIOBASE resolution	Agriculture: 54% reduction CH_4, 25% reduction N_2O Energy: 79% reduction CH_4 Waste: 29% reduction CH_4	Agriculture: Frank et al. (2019) Waste, energy: IMAGE 3.2, RCP 1.9, CMIP6: Gidden et al. (2019)
12	IOT	Income elasticities of demand	49 EXIOBASE regions	Map to EXIOBASE products	N/A	Bjelle et al. (2021)

Vuuren et al., 2017). Data for SSP1 basic elements and RCP trajectories were extracted from the IMAGE USS 3.2 data package (Stehfest et al., 2014), and CMIP6 emissions data on the decarbonization of transportation modes were extracted from the International Institute for Applied Systems Analysis (IIASA) SSP scenario database (Gidden et al., 2019). Data were collected from literature for total factor productivity development (Leimbach et al., 2017) and for CH_4 and N_2O abatement in agriculture and waste (Frank et al., 2019) because of the more specific country- and sector-level detail available.

The scenario model is built from the EXIOBASE multi-regional supply-use table (MRSUT), version 3.8.2 (Stadler et al., 2021). EXIOBASE covers all European Union countries and major EU trade partners, the focus of our analysis, and has high product and sector resolution, linking 163 industries, 200 product categories, and territorial greenhouse gas (GHG) accounts for all 27 EU member countries, 17 major economies, and five Rest of World (RoW) regions (Stadler et al., 2018). We selected 2015 as the baseline year because it is the most recent year with observed energy impacts available in EXIOBASE.

In some cases, conversion was required to translate changes to physical energy flows to the SUT's monetary units. Conversion factors for energy carriers were calculated using emission factors for CO_2, CH_4, and N_2O from the IPCC Emission Factor Database (IPCC, 2021) and extended energy accounts from EXIOBASE.

2.2. Building the scenario model

2.2.1. Implementing changes to the supply-use tables

We developed our scenario model by perturbing various components of a global environmentally extended SUT framework according to the scenario specifications. The intention was to remain as close as possible to the specifications of the 1.5°C-compatible mitigation pathway, except for the lack of household lifestyle change that characterizes this scenario.

Our approach is an extension of the method developed by de Koning et al. (2016). The core of the modeling revolves around scaling the supply and use flows and the environmental extensions with 'change ratios' that represent a specific socioeconomic or technological change in the scenario. This change ratio is the ratio of the scenario-year value to the baseline-year value for each scenario element. These change ratios could represent a linear change, such as scaling the entire framework for population change, but could also represent a discontinuous change where the supply or intermediate use of one sector is fully or partially replaced by another. Following de Koning et al. (2016), scenario models were constructed using constant basic prices (year 2015) to avoid changes to relative prices. The model was created in five-year intervals, using the base year supply-use table for individual economies as the starting point for each year.

Each socioeconomic or technological change was individually applied to the MRSUT in the order outlined in Table 1. To account for any interrelated scenario dynamics, each modeling step after initialization was implemented on the supply-use table from the previous step. For instance, total factor productivity (TFP) and population growth contribute to gross domestic product (GDP) growth. To account for this in the supply-use tables, we accounted for any increase in GDP achieved through population or TFP growth and scaled the change factors according to this residual change. We modeled the change in GDP from value added generated by the agricultural, industrial, and service sectors relative to the total economy specified in our scenario. This required adjusting the three initial change ratios to reflect the remaining relative change, before applying the adjusted change ratios to corresponding industries across supply and use tables, value added, and extensions. We scaled the total final demand to match the total value added before proceeding with balancing supply and use tables.

We modeled changes in industry technology and emissions based on sector-specific emission pathways. Any changes in CO_2 emissions for a sector in a scenario year, relative to the baseline year, suggested a shift in fossil fuel use inputs. To account for these changes, we adjusted fossil fuel inputs to align with the CO_2 combustion emissions pathway for each sector. We considered the substitution of alternate energy sources, such as electricity or biofuels, assuming that a corresponding monetary or physical energy quantity of low-carbon technology replaced a share of the previous fossil fuel use. The resulting technological adjustments were scaled to reflect the changes in direct sector emissions across the economy. Non-CO_2 emissions were scaled according to the scenario parameters, without contributing to fuel shift calculations.

Emissions from the direct consumption of fuel sources by households and other final users were modified to match changes to final demand. Linear scaling directly using the change ratios was applied to reflect an average increase or decrease in total final demand. In cases where final demand adjustments changed the relative share of fossil fuel consumption, such as from industrialization or changing technology, conversion factors were used to scale direct emissions to reflect the new final demand expenditures.

For most modeling steps, a sufficiently detailed value was available to implement the SUT changes. However, only aggregated regional electricity values were available for modeling the energy system shift. We addressed this by downscaling the aggregated electricity values to the individual countries in EXIOBASE using the starting shares of electricity in each region to calculate the target future mix. Prices were calculated by dividing the total monetary supply in 2015 basic prices by the total physical supply reported by the IEA in the corresponding year. These prices were used to convert the physical electricity values to the monetary units used in the SUT.

To maintain consistency within the SUT framework, balancing algorithms were systematically applied after the alternations of each step. The SUT-RAS method of Temurshoev and Timmer (2011) is a version of the RAS repetitive scaling method commonly used for updating IOTs that does not require total supply and use product totals and is thus used for projecting time series of MRSUTs such as WIOD (Dietzenbacher et al., 2013). The SUT-RAS balancing technique was applied following each step to balance industry input and output and total supply and use of each SUT, which also captures downstream changes to the economy. For compiling the multi-regional SUT from individual SUTs, we harmonized global imports and exports while maintaining trade patterns from the base year when possible, and balanced the system using the GRAS method (Temurshoev et al., 2013), following de Koning et al. (2016). The balanced country-level SUTs were combined into a multi-regional SUT following all balancing procedures and then converted to a global input-output table using an industry technology assumption (Eurostat, 2008).

2.2.2. *Adjusting final demand expenditures*

After implementing changes from SSP1-RCP1.9 to the supply-use tables, household final demand expenditures in 2050 largely reflect the expenditure patterns of 2015, aside from the changes embedded in the electricity system or resulting from a change in economic composition. To better reflect final demand expenditure from increasing household income, household expenditures on individual final demand categories were adjusted based on income elasticities. Income elasticity represents the change in demand from a given change in income. We used income elasticities of demand for 15 product categories in the 49 EXIOBASE regions calculated by Bjelle et al. (2021). This represents a very simplified demand system, but this simplification is in line with other model assumptions that assume linear scaling and no price effects. Total household final demand expenditure per capita was assumed to be a reasonable proxy for change in income per capita, as savings patterns or investments were not specifically altered in this scenario. Estimated final demand expenditures were calculated from the income elasticities (Eq. (1)):

$$y^{t}_{hh,i} = y^{2015}_{hh,i} + \left(\varepsilon_i \Delta y_{hh}\, y^{2015}_{hh,i}\right) \tag{1}$$

Where $y^{t}_{hh,i}$ is the estimated demand for an EXIOBASE product i in scenario year t, ε_i is the income elasticity of demand for product i, Δy_{hh} is the relative change in total household demand between the baseline year 2015 and scenario year t, and $y^{2015}_{hh,i}$ is the demand for an EXIOBASE product i in the baseline year 2015.

The estimated final demand expenditures $y^{t}_{hh,i}$ were converted to household budget shares for all products, which were then used to adjust the household expenditures on products while maintaining the original total household expenditure.

Final demand expenditure on electricity categories was kept constant from the previous step to remain consistent with the electricity consumption determined by the exogenous scenario parameters. The household direct emissions were scaled to reflect adjusted final demand expenditures on energy carriers using the approach applied for adjusting emissions within the SUT framework, described in the previous section.

2.2.3. *Sensitivity analysis*

To understand the effect of each modeling step on household emissions, we conducted a sensitivity analysis that excluded one modeling step while implementing others normally. We compared the resulting emissions to those in our fully implemented scenario.

2.3. *Conversion of supply-use tables and the calculation of carbon footprints through environmentally extended input-output analysis*

Household carbon footprints, the GHG emissions attributed to final household consumption activities, comprise the indirect emissions necessary for the production of final consumption as well as direct emissions from fossil fuel combustion at the household level (Hertwich and Wood, 2018). Household carbon footprints can be calculated by applying the Leontief demand-driven model to define environmental stressors as a function of final demand (Miller and Blair, 2009).

As supply-use tables and corresponding emissions accounts correspond to production-based accounts, a transformation of these tables is required to attribute changes in the electricity mix, production efficiency, and fuel types to the impacts associated with final consumption. Transforming the multi-regional SUT into an environmentally extended multi-regional input-output (MRIO) model following the principles described in Eurostat (2008) allows for global emissions to be attributed to final consumption activities rather than industrial production. To create the direct requirements matrix of input-output coefficients (A) using the industry technology assumption, the use table is multiplied by a transformation matrix and the inverse of a diagonalized vector of product output. The transformation matrix represents the fixed market share of each industry to product output as the supply table multiplied by the inverse of a diagonalized vector of industry output.

The indirect emissions of a footprint are calculated as the dot product of the direct intensity matrix of emissions coefficients S (emissions per monetary unit of output), the Leontief inverse matrix L (embodied production demands associated with expenditure on a good, calculated as $(I - A)^{-1}$, where direct requirements matrix A contains inter-industry input-output coefficients and I is an identity matrix of the corresponding size), and household final demand y_{hh}. Direct household emissions coefficients $S_{y,hh}$ are multiplied by household final demand and added to indirect emissions for the total household carbon footprint e_{hh}. The emissions intensities of final demand, $S \bullet L$, provide insight into the potential total environmental impacts per unit change of final demand.

Household carbon footprints calculated with the Leontief demand-driven model are represented as follows (Eq. (2)):

$$\mathrm{e_{hh}} = (\mathrm{S} \bullet L \bullet \mathrm{y_{hh}}) + \left(\mathrm{S}_{y,hh} \bullet \mathrm{y_{hh}}\right) \tag{2}$$

Regional aggregation for analysis was performed after calculating the individual country footprints.

For our emissions coefficients (S and $S_{y,hh}$), we included all emission extensions for all major greenhouse gases (CO_2, CH_4, N_2O, SF_6, HFCs, and PFCs) from combustion and non-combustion sources from mining, agriculture (excluding land use change) and waste available in EXIOBASE. We converted GHG emission values to CO_2-equivalents (CO_2e) using the IPCC AR6 global warming potentials with a 100-year time horizon (GWP100) (IPCC, 2022).

2.4. Emissions benchmarks in 2030 and 2050

We calculated household emissions for 2030 and 2050 consistent with established 1.5°C emissions pathways to use as a benchmark for our Decarbonization Divergence scenario. Median global emissions for 1.5°C-compatible pathways in the IPCC AR6 are 31 $GtCO_2e$/year in 2030 and 9 $GtCO_2e$/year in 2050 (Riahi et al., 2022). We divided the total global emissions in 2030 and 2050 by the corresponding SSP1 population levels to arrive at an equal global per-capita total footprint benchmark value (Table 2).

Two household emissions benchmark values were calculated from the total emissions benchmark: one using a global average share of household emissions over 2015–2050 (63%) to allocate a standard share of emissions to households, and the other using the average share of household emissions per country for a differentiated set of targets (Table S3). Unless indicated otherwise, the targets discussed in this paper refer to the global average benchmark.

3. Results

3.1. Household carbon footprints in 2030 and 2050 compared to 1.5°C targets

Household emissions will generally not be compatible with a 1.5°C emissions trajectory with only background system decarbonization by scenario year 2050 (Table 2, Fig. 1). However, the rapid decarbonization efforts between 2020 and 2030 that are characteristic of IMAGE's SSP1-RCP1.9 mitigation scenario combined with the less-stringent target allow for some countries to remain on a 1.5°C pathway in 2030 without concerted household lifestyle change.

Table 2

Emissions benchmarks for household carbon footprints in 2030 and 2050 (tCO_2/cap), reflecting the 25th, 50th, and 75th percentiles of emissions compatible with 1.5°C mitigation pathways, as presented in IPCC AR6. The benchmarks calculated from the emissions corresponding to the 50th percentile of emissions pathways are the default used in this paper.

Scenario year	2030			2050		
Percentile, mitigation pathway scenarios	25th	50th	75th	25th	50th	75th
Total emissions benchmark (tCO_2e/cap)	4.11	3.77	3.45	1.30	0.97	0.65
Household emissions benchmark (tCO_2e/cap)	2.60	2.38	2.16	0.82	0.61	0.34

In scenario year 2030, eight EXIOBASE regions are projected to have household footprints below the 1.5°C global threshold in 2030 (Fig. 1): India (1.16 tCO_2e/cap), China (1.45 tCO_2e/cap), RoW Asia (1.63 tCO_2e/cap), RoW Africa (1.87 tCO_2e/cap), Slovakia (2.11 tCO_2e/cap), Indonesia (2.19 tCO_2e/cap), Croatia (2.22 tCO_2e/cap), and Slovenia (2.36 tCO_2e/cap). These countries' footprints, aside from China and Slovakia, are also within their respective differentiated household emissions targets in 2030. Mexico (2.74 tCO_2e/cap), Brazil (2.86 tCO_2e/cap), and Romania (2.86 tCO_2e/cap) are within the household emissions targets for their respective countries but do not meet the global-level threshold due to the larger share of emissions from households compared to non-profit organizations, governments, or investments, relative to other countries. No countries are projected to meet the 2050 household emissions target. The smallest household footprints in 2050 in our baseline scenario are for China (1.06 tCO_2e/cap), India (1.1 tCO_2e/cap), Slovakia (1.47 tCO_2e/cap), Bulgaria (1.6 tCO_2e/cap), and Turkey (1.64 tCO_2e/cap).

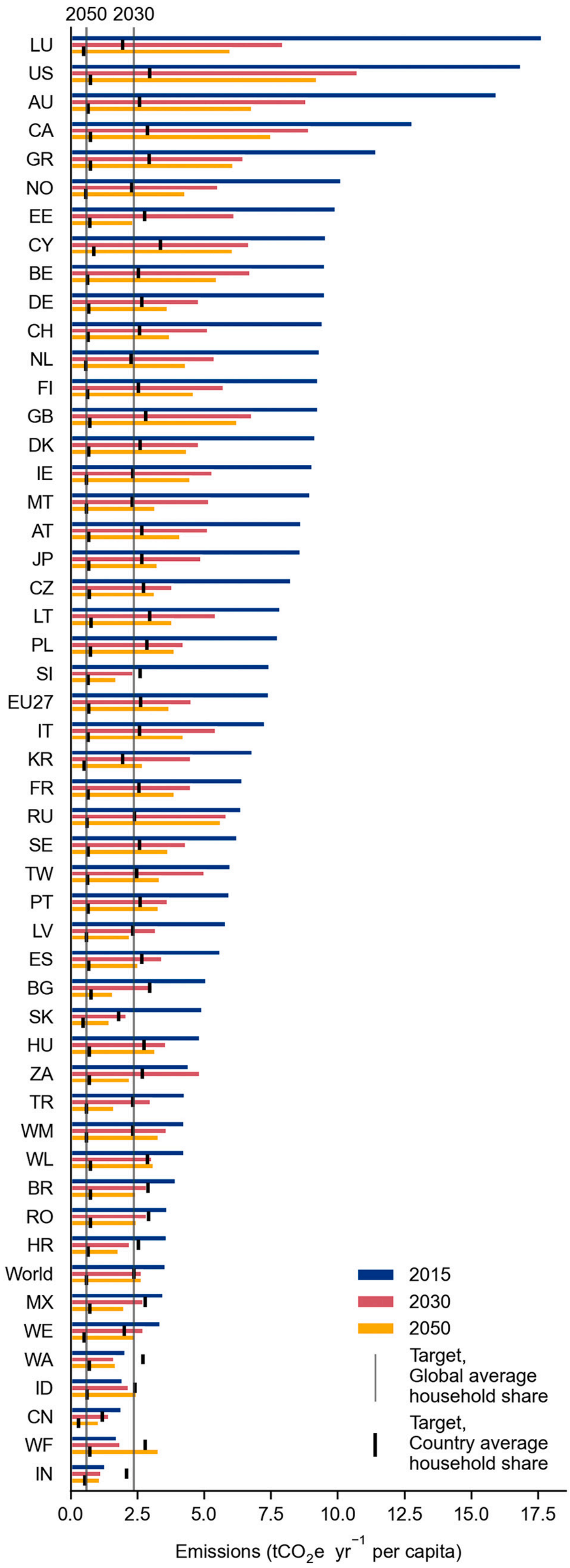
3.2. Household carbon footprint development

Even without explicit household lifestyle change, the average household footprint in most countries decreased from 2015 levels (Fig. 1). In the EU27, household per-capita footprints are highest in 2015 (7.44 tCO_2e) and decrease most rapidly between 2020 and 2030 (4.54 tCO_2e) before reaching the lowest value in 2050 (3.7 tCO_2e, −50% from 2015). Footprints decrease for each country in the EU27. However, EU27 countries starting with larger footprints tend to remain the countries with the largest footprints in 2050. We observe the greatest reduction in Slovenia (77%), although the country starts with an average footprint. Romania has one of the lowest 2015 household footprints in the EU27 (3.62 tCO_2e/cap) and one of the smallest reductions through 2050 (−31%, to 2.49 tCO_2e/cap). Regional differences in footprints also decrease, as initial footprints in Western and Eastern EU regions differ by more than 2 tCO_2e/cap in the starting year but converge to a difference of less than 1 tCO_2e/cap by 2050.

On a global level, we observe an absolute decrease in the global average household carbon footprint from the 3.56 tCO_2e/cap baseline value in each scenario year (Table S1). The global population-weighted average per-capita household footprint does not follow a strictly linear reduction. The global average footprint decreases to 2.67 tCO_2e by 2030, before decreasing further to 2.48 tCO_2e in 2040 and rebounding back to 2.67 tCO_2e in 2050 (−25% from 2015). This pattern also exists on an absolute level, as global household emissions decrease from 26.2 $GtCO_2e$ in 2015 to 21.5 $GtCO_2e$ in 2030 before slightly increasing to 22.6 $GtCO_2e$ in 2050 (Fig. 5). Of countries where the household footprint decreases, the average reduction by 2050 is 48%. However, household footprints increase from the baseline year in seven countries and regions, where increasing consumption due to a low starting GDP outpaces technological development.

3.3. Scenario emissions compared to 1.5°C benchmark

On a global level, the majority (75%) of the necessary household footprint reductions to reach the 2030 1.5°C-compatible target of 2.38 tCO_2e/cap are achieved by technological changes (Fig. 2). This is also true at the EU level, although to a smaller extent (2.2 tCO_2e/cap, 57%). By 2050, a larger share (2.0 tCO_2e/cap, 70%) of global emissions is unmitigated, whereas the EU27 technological mitigation share is similar to 2030 (3.7 tCO_2e/cap, 55%). As the global footprint reduction stagnates due to rising household expenditure while the target becomes more stringent in 2050, the majority of global emissions reductions beyond 2030 will need to be achieved from other mitigation



(caption on next column)

Fig. 1. Per-capita household carbon footprints in 2015, 2030, and 2050 for 49 countries and regions of EXIOBASE and the EU27 and global average, ordered by descending total emissions in 2015. Vertical lines indicate thresholds for 1.5°C in 2030 and 2050: the continuous lines (grey) represent a universal global target calculated using the global average household share of emissions, and the thicker individual lines (black) represent differentiated targets calculated for individual countries using the share of household emissions in total emissions for each country. Countries are identified by ISO2 code; aggregated regions identified by EXIOBASE code: WA, RoW Asia and Pacific; WE, RoW Europe; WF, RoW Africa; WL, RoW America; WM, RoW Middle East.

interventions beyond the decarbonization efforts modeled in this scenario.

3.4. Contribution and drivers of EU27 household carbon footprint

Carbon footprints can be altered by changes to the emissions intensities associated with the final demand of a product category, direct emissions from final demand activities, and total final demand expenditure (see Eq. (2)). Our scenario model primarily decreases emissions intensities embedded in consumption by reducing fossil fuel inputs and the associated emissions for industrial production. Emissions multipliers for total final demand – calculated from the emissions intensities weighted proportionally by final demand category and origin – are projected to decrease globally by a factor of 5 in 2050 (Fig. 3). Within the EU27, the weighted final demand multipliers ranged between 0.18–0.94 $kgCO_2e/EUR$ in 2015, decreasing to 0.022–0.36 $kgCO_2e/EUR$ in 2050. Reductions in emissions intensities for household demand were difficult to accomplish with limited household consumption of renewable energy technology in the baseline year. Such was the case for Czechia, the EU27 country with the greatest observed emissions intensity of household final demand in 2015. However, as the energy system transformation would be accounted for in purchased products, a 60% reduction from 2015 was still possible.

The decrease in emissions intensity contributes to changes in the composition of carbon footprints across the EU27. Across all products and countries, emissions intensities are expected to decrease an average of 79% from 2015 until 2050, with the largest average decreases in clothing (90%) and services (85%), and the smallest in housing (67%). These reductions are observed in the changing composition of the EU household footprint (Fig. 4). Emissions attributed to energy and food consumption have a relatively constant share in the EU27 household carbon footprint, as other sectors decarbonize more profoundly, or household consumption decreases relative to 2015. Indirect emissions for household energy decrease relative to the baseline but together still constitute a large share of household emissions in the EU, especially from district heating emissions in the Eastern EU countries. In the EU27, indirect household emissions in scenario years modeled decrease relative to 2015, while direct emissions from household energy needs slightly increase. The average share of direct emissions in the EU27 household footprint rises from 19% in 2015 to 31% in 2030 and 43% by 2050, and absolute direct emissions increase in all EU27 regions aside from Eastern EU.

Similar product categories contribute to the household carbon footprints across the scenario years. From 2015 to 2030 and 2050, the top 10 categories contributing to total consumption emissions remained relatively stable, with seven of the same contributors across the three years (Table 3). Emission mitigation is particularly evident in some high-contribution products. Electricity from coal is phased out of the electricity mix and remaining emissions are widely mitigated. Emission reduction targets for aviation and maritime transport are achieved by replacing a share of fossil fuels with bio-based fuels. However, aviation emissions are still one of the major contributors to the EU27 household footprint in 2050 with 1.7% of the total, directly following cattle products.

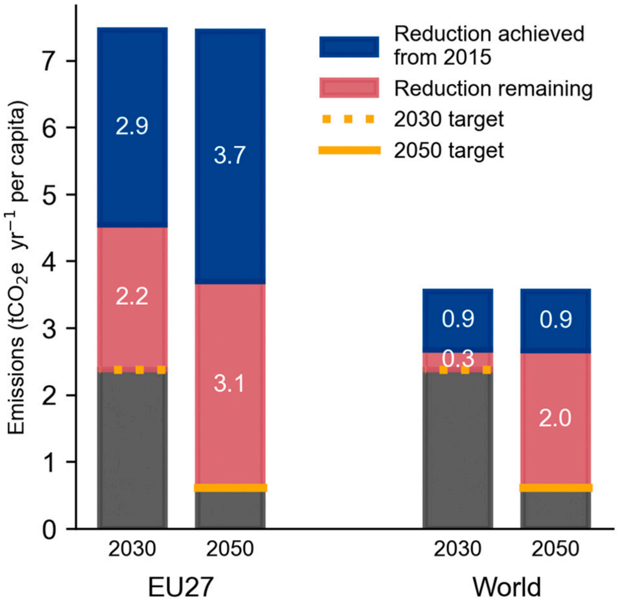


Fig. 2. Total household footprint reductions achieved from 2015 through background system changes and emissions reduction remaining in 2030 and 2050 to be compatible with a 1.5°C target, global and EU27 average.

3.5. Sensitivity analysis

Excluding population change and GDP change with sector shift caused emissions to decrease relative to the scenario results in 2030 and 2050 (Fig. 5), indicating that these steps cause the largest emissions increases in our scenario in 2050. Excluding changes to demand shift and building heating also slightly decreased emissions relative to the scenario model in 2030 and 2050, respectively. The sensitivity analysis which excluded total factor productivity projected the highest household emissions level in 2050, with nearly double the emissions of both the 2015 baseline and the full scenario. Excluding changes to building heating and non-CO_2 emissions had a larger impact in 2030, and aviation had a larger impact in 2050. The sensitivity analysis that excluded any changes to buildings resulted in slightly lower emissions in 2050 compared to the default scenario, despite the strong opposite effect in 2030. As emission reduction practices are adopted by industrial sectors in other modeling steps and no changes are made to household final demand, the changes from carbon capture and storage (CCS) or more renewables in the electricity mix are small.

4. Discussion

4.1. Validation of background system reduction potential

Our results suggest that implementing widespread technological changes can offer moderate emissions reductions in the context of economic growth and other emissions drivers. On a global level, we find that non-technological interventions will need to comprise approximately 70% of the emissions reduction required to limit global warming to 1.5°C. Analysis by the IPCC of the reduction potential of demand-side changes estimates that demand-side changes can reduce total emissions in the transport, food, and building sectors by 40–70% by 2050 (Creutzig et al., 2022). As our scenario implies that the required level of lifestyle change would approach its estimated maximum, a question arises regarding the potential for additional emissions reduction. The possibility of further reduction through additional technological development, negative emissions technologies, or a decrease in final demand expenditure is discussed below.

Given the modest (25%) total potential global emission reduction

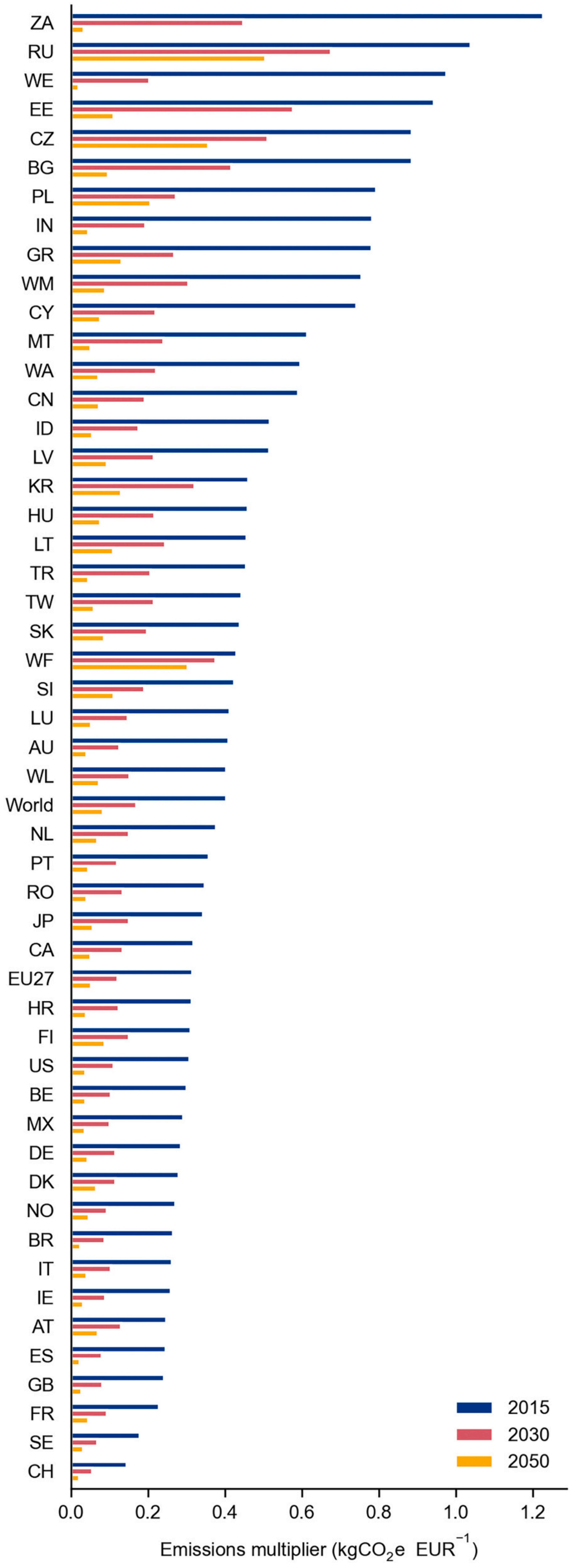
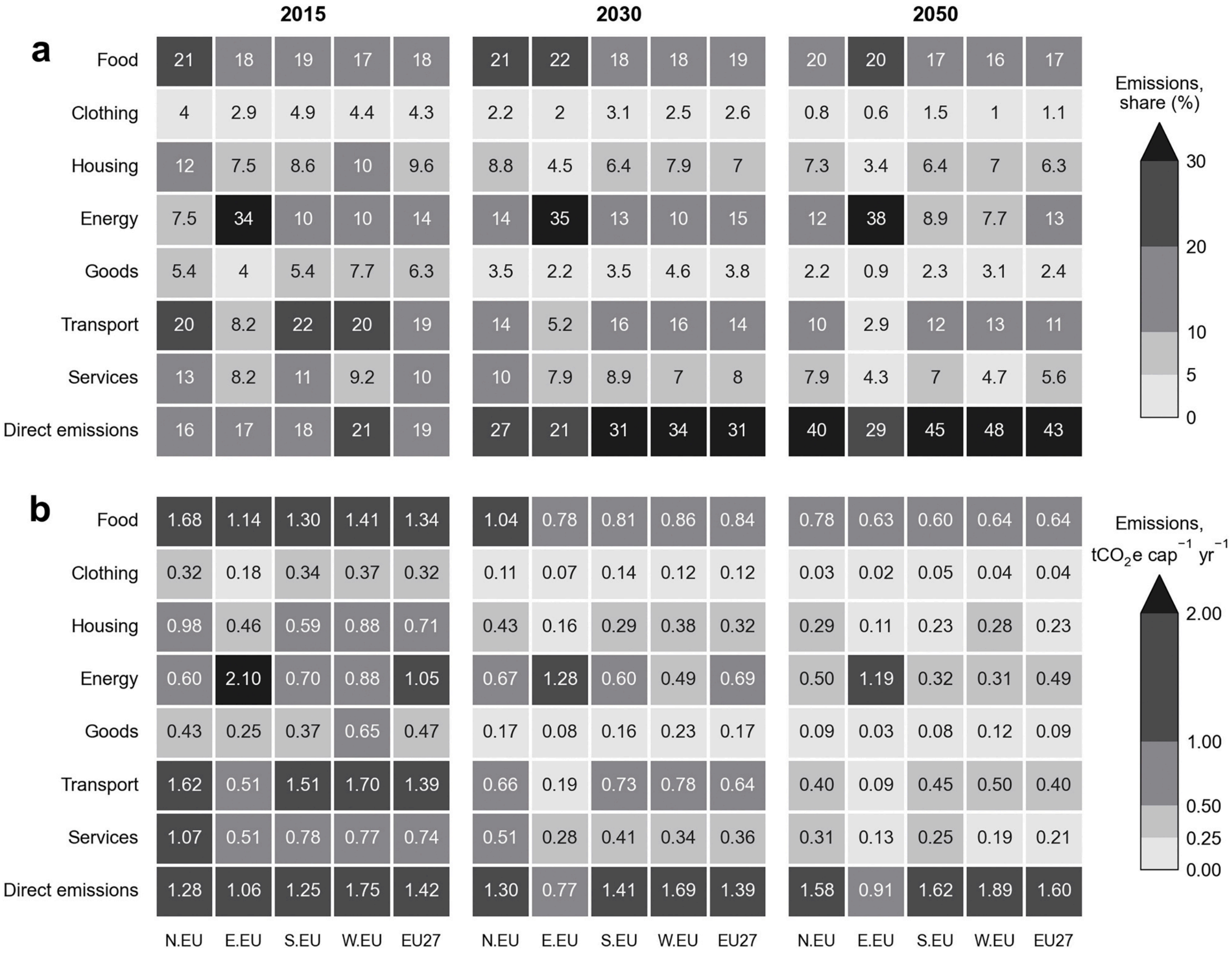


Fig. 3. Emissions intensity multipliers for final consumption expenditure by households in $kgCO_2e$/EUR in 2015, 2030, and 2050 for 49 countries and regions of EXIOBASE and the EU27 and global average, ordered by descending emissions intensity multiplier in 2015. Countries are identified by ISO2 code; aggregated regions identified by EXIOBASE code: WA, RoW Asia and Pacific; WE, RoW Europe; WF, RoW Africa; WL, RoW America; WM, RoW Middle East.



a

	2015 N.EU	2015 E.EU	2015 S.EU	2015 W.EU	2015 EU27	2030 N.EU	2030 E.EU	2030 S.EU	2030 W.EU	2030 EU27	2050 N.EU	2050 E.EU	2050 S.EU	2050 W.EU	2050 EU27
Food	21	18	19	17	18	21	22	18	18	19	20	20	17	16	17
Clothing	4	2.9	4.9	4.4	4.3	2.2	2	3.1	2.5	2.6	0.8	0.6	1.5	1	1.1
Housing	12	7.5	8.6	10	9.6	8.8	4.5	6.4	7.9	7	7.3	3.4	6.4	7	6.3
Energy	7.5	34	10	10	14	14	35	13	10	15	12	38	8.9	7.7	13
Goods	5.4	4	5.4	7.7	6.3	3.5	2.2	3.5	4.6	3.8	2.2	0.9	2.3	3.1	2.4
Transport	20	8.2	22	20	19	14	5.2	16	16	14	10	2.9	12	13	11
Services	13	8.2	11	9.2	10	10	7.9	8.9	7	8	7.9	4.3	7	4.7	5.6
Direct emissions	16	17	18	21	19	27	21	31	34	31	40	29	45	48	43

b

	2015 N.EU	2015 E.EU	2015 S.EU	2015 W.EU	2015 EU27	2030 N.EU	2030 E.EU	2030 S.EU	2030 W.EU	2030 EU27	2050 N.EU	2050 E.EU	2050 S.EU	2050 W.EU	2050 EU27
Food	1.68	1.14	1.30	1.41	1.34	1.04	0.78	0.81	0.86	0.84	0.78	0.63	0.60	0.64	0.64
Clothing	0.32	0.18	0.34	0.37	0.32	0.11	0.07	0.14	0.12	0.12	0.03	0.02	0.05	0.04	0.04
Housing	0.98	0.46	0.59	0.88	0.71	0.43	0.16	0.29	0.38	0.32	0.29	0.11	0.23	0.28	0.23
Energy	0.60	2.10	0.70	0.88	1.05	0.67	1.28	0.60	0.49	0.69	0.50	1.19	0.32	0.31	0.49
Goods	0.43	0.25	0.37	0.65	0.47	0.17	0.08	0.16	0.23	0.17	0.09	0.03	0.08	0.12	0.09
Transport	1.62	0.51	1.51	1.70	1.39	0.66	0.19	0.73	0.78	0.64	0.40	0.09	0.45	0.50	0.40
Services	1.07	0.51	0.78	0.77	0.74	0.51	0.28	0.41	0.34	0.36	0.31	0.13	0.25	0.19	0.21
Direct emissions	1.28	1.06	1.25	1.75	1.42	1.30	0.77	1.41	1.69	1.39	1.58	0.91	1.62	1.89	1.60

Fig. 4. Contribution of major consumption categories to carbon footprints of EU27 households. (a) Contribution by percent of total emissions. (b) Absolute emissions per aggregated product category (tCO_2e/cap). N.EU, Northern EU; E.EU, Eastern EU; S.EU, Southern EU; W.EU, Western EU; EU27, European Union average.

Table 3

Emissions from the top 10 contributing categories to carbon footprints in the EU27 in 2015, 2030, and 2050. Emissions per category are presented as an absolute value (tCO_2e) and percentage of total footprint, and in descending order from 2015. A dash (–) in a column indicates that the category was not part of the top 10 contributing sectors in that year. The EXIOBASE abbreviation 'nec' refers to 'not elsewhere classified'.

EXIOBASE Product/ consumption category	Emissions per category (tCO_2e/cap)			Emissions share of total footprint (%)		
	2015	2030	2050	2015	2030	2050
Direct emissions	1.42	1.39	1.60	19.1	30.7	43.3
Steam and hot water supply services	0.35	0.21	0.23	4.7	4.6	6.2
Food products nec	0.33	0.18	0.12	4.5	4.0	3.1
Motor Gasoline	0.31	0.14	0.09	4.1	3.0	2.3
Air transport services	0.28	0.14	–	3.8	3.0	–
Electricity by coal	0.27	0.10	–	3.6	2.2	–
Hotel and restaurant services	0.24	0.13	0.08	3.3	2.8	2.2
Real estate services	0.24	0.11	0.08	3.2	2.4	2.0
Dairy products	0.23	0.14	0.11	3.0	3.1	2.9
Sea and coastal water transportation services	0.17	–	–	2.2	–	–
Products of meat cattle	–	–	0.06	–	–	1.7
Distribution and trade services of electricity	–	0.16	0.10	–	3.4	2.8
Distribution services of gaseous fuels through mains	–	–	0.08	–	–	2.1

from 2015 (Table S1), it seems reasonable to investigate further reduction through technology. We implemented the maximum feasible technological change for sectors explicitly indicated by the IMAGE SSP1-RCP1.9 scenario model. Further technological mitigation potential for the steps included in this model would be a primarily theoretical exercise given the end year of 2050. Our scenario results indicate an approximately 5-fold decrease in global weighted average emissions intensity (Fig. 3). This is not sufficient to maintain expenditure growth; previous analysis has indicated that an 8.5-factor reduction in global emissions intensities would be required for a high-income EU country to remain on a 1.5°C trajectory with constant consumption levels (Bjørn et al., 2018). Additional mitigation actions not currently included but likely promising for climate change mitigation include the use of secondary inputs and electric arc furnaces for steel (de Koning et al., 2016), circular economy efforts (Donati et al., 2020; Wiebe et al., 2019), and more specific productivity initiatives in agriculture.

Carbon dioxide removal technologies are a feature of many 1.5°C scenarios modeled by IAMs, including the pathway that forms the basis of our scenario (van Vuuren et al., 2018). We included the uptake of CCS for fossil fuel combustion in industry and electricity production and bioenergy (without CCS) in this scenario model. We did not account for negative emissions, as we believe this modeling choice better highlighted the upper limit of known technological reduction potential. Accounting for negative emissions in this scenario model would allow for a slower dissemination of technological change or a lower uptake of sustainable lifestyle change. However, relying on negative emissions

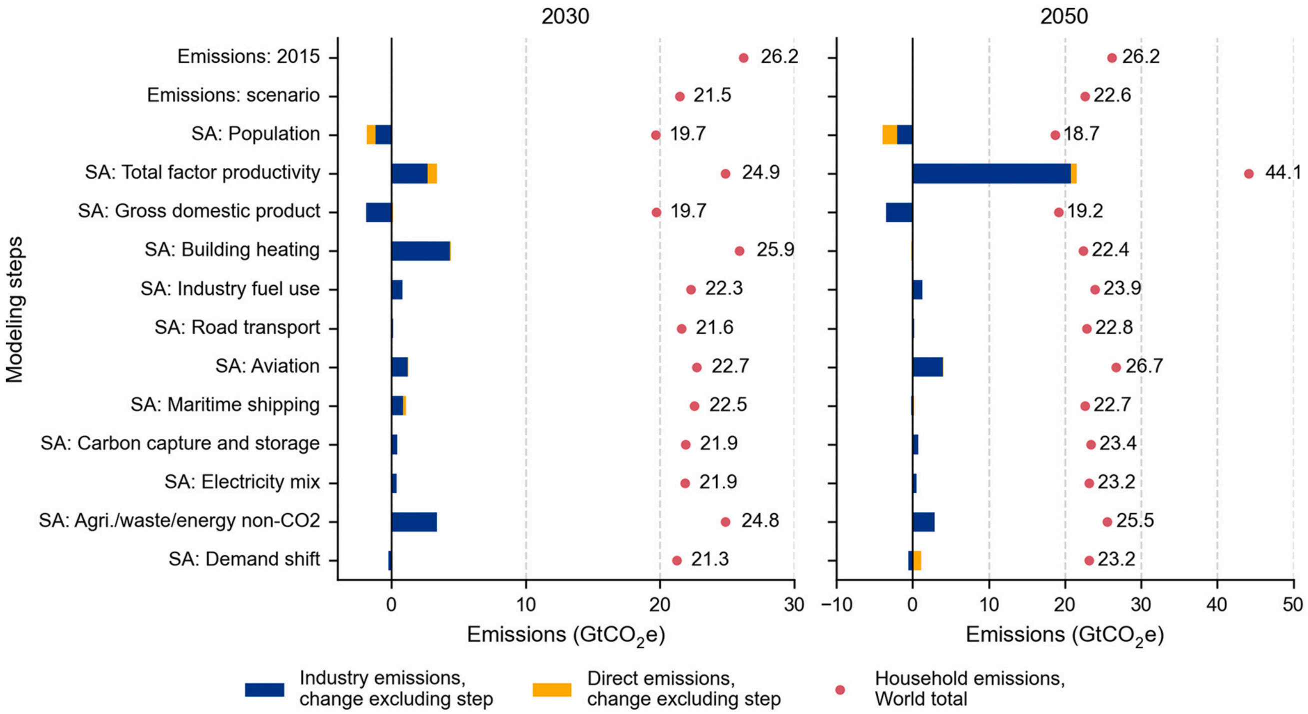


Fig. 5. Global household emissions in 2015 and scenario emissions in 2030 and 2050 compared to emissions from a sensitivity analysis (SA) that leaves out each modeling step in turn while executing other steps normally. Changes to industry and direct emissions from leaving out each step are compared to emissions from the scenario model that includes all modeling steps.

technologies poses considerable risks, and widespread adoption of sufficiency lifestyles could reduce the demand for these technologies (Grubler et al., 2018). We did not deviate from the levels of bioenergy or CCS in industry to account for risks, as we aimed to reproduce SSP1-RCP1.9 assumptions about technological development. Reducing the deployment of these technologies in the scenario model with all else equal would increase emissions intensities and carbon footprints.

Finally, reduced final demand expenditure may be the most straightforward option for reducing household footprints, given that footprints are a function of final demand. Reduced economic growth would be necessary for 1.5°C-compatible emissions reduction without exposure to large uncertainty of technological development (Keyßer and Lenzen, 2021). Our scenario was based on the second-highest level of economic growth of the SSPs, which is theoretically compatible with low mitigation and adaptation challenges. Decoupling energy use from GDP has rarely been observed in practice (Haberl et al., 2020), and economy-wide implications from energy efficiency are seldom considered in dynamic models (Brockway et al., 2021), much less a static input-output model. Our model shows the maximum potential for technological mitigation under high economic growth conditions based on the feasibility of technological deployment assumed in the IMAGE SSP1-RCP1.9 pathway.

4.2. Policy implications

We find that even with extensive reductions in emission intensities, emissions approaching 3 tCO_2e/cap will need to be mitigated in the EU27 to limit global warming to 1.5°C. Although considerable reductions are possible in the energy and industry domains, the current largest structural contributors to the EU27 household carbon footprints will remain stable. Unmitigated household direct emissions and select product categories with a combination of high demand and high emissions intensity will continue to make up the majority of future carbon footprints. Initiatives to reduce direct household consumption of fossil fuels for heating, cooking, and mobility can reduce approximately 40% of future EU footprints if rebound effects can be avoided. Further reductions are also possible when considering upstream production impacts. Mitigation efforts that limit demand or promote alternatives to emission-intensive products such as air travel or meat and dairy foods may also need to be considered, as the technological decarbonization potential will not exceed demand growth in these sectors (Bryngelsson et al., 2016; Sacchi et al., 2023).

Our approach to benchmarking emissions in a single year does not account for the dynamic effects of over- or under-shooting an emissions target. The relatively greater emissions reductions between 2020–2030 compared to 2030–2050 in our scenario differ from the pathways to achieve the European Green Deal targets of 55% reduction from 1990 levels by 2030 and net-zero emissions by 2050. When calculated with our SSP1 scenario population, the European Commission's emission reduction pathways indicate per-capita emissions reductions of 41% from 2015 levels by 2030 and 100% (net-zero) by 2050 (European Commission, 2021). The emissions thresholds for the EU27 presented in this paper require a 68% reduction from 2015 levels by 2030 and 92% by 2050. While changes to footprints are not directly comparable to changes to territorial emissions due to the effects of trade and varying rates of decarbonization across regions, the comparison can still highlight the differing emissions timelines of an IPCC 1.5°C-compatible scenario and EU emissions mitigation timelines. Thus, our scenario comparatively overestimates EU27 overshoots in 2030 and underestimates them in 2050.

The equal per-capita emissions targets used in this paper can be interpreted as quite unequal when accounting for historical equality rather than solely annual parity. Cumulative emissions equality has strong ethical arguments in its favor due to the inequality of historical emissions levels between the Global North and Global South and the association of emissions, economic growth, and human development (Hickel, 2020; Neumayer, 2000). Even with the EU27 achieving net-zero emissions by 2050, the region would exceed a cumulatively equal 1.5°C budget by 20%, a consequence of surpassing its emissions budget around 1990 (Fanning and Hickel, 2023). A more reasonable approach might account not only for the past overconsumption of the global emissions budget but also for the maximum feasible reduction levels. Even so, this would result in negative emissions budgets for 19 EU countries (Williges et al., 2022). Accounting for historical emissions would mean that the emissions overshoots for the EU27 presented here are underestimated. Yet, the lack of scenarios indicating an immediate reduction of EU27 emissions to net zero underscores the speculative nature of such a target.

4.3. Limitations and future development

Future scenario development in either an MRSUT or IO framework has some inherent limitations regarding uncertainty and novel technology representation. Building a scenario in an MRSUT framework rather than IAM enables the representation of specific technological development in greater detail. However, the introduction of novel technologies to an economy can pose a challenge in a SUT or IO model. When a smaller economy lacks data for domestic production of some technology in the baseline year, this absence will be propagated through the future economy if modeling involves multiplying existing coefficients by a scalar. Similar SUT-based scenario models such as de Koning et al. (2016) and Wiebe et al. (2018) also do not specify new input coefficients for novel technologies absent from the base SUT. As more data are available for aggregated regions, these models may have a lower need for this compared to this study with its greater geographical resolution. Practically, missing energy system technologies have the most impact in this scenario. Our approach to downscaling the aggregated electricity scenario data inputs from IMAGE ensured a domestically appropriate level of renewable electricity, and all plausible fossil fuel inputs were considered when adjusting fossil input to industry. However, future IO scenario models may wish to improve the detail with which novel technologies are represented, as it is possible on a limited scale to define coefficients for new technologies (Wilting et al., 2008; Wimmer et al., 2023).

Adding greater resolution to household expenditure variation from sociodemographic factors could provide greater insight into future consumption patterns and impacts. We present average household footprints here, but footprints may vary based on factors such as income group or degree of urbanization. Explicit income redistribution in the EU may decrease overall emissions due to the relatively higher emissions intensity of high-income EU households (Ivanova and Wood, 2020). Moving from rural areas to towns and from rural areas to cities can reduce EU footprints by 3% and 7%, respectively (Ottelin et al., 2019), as urbanization can encourage lifestyle change due to more access to public transportation and lower space heating emissions from different housing types (Munoz et al., 2020). These factors are likely minor compared to major drivers such as increasing GDP per capita (Fig. 5). However, future scenario models that incorporate sociodemographic influences on footprints can provide a richer understanding of future footprint development and heterogeneous mitigation burdens.

5. Conclusions

Overall, this research contributes to the growing support for extensive demand-side mitigation to mitigate the risks of supply-side technology failing to achieve the necessary emissions reduction for 1.5°C. The prospective scenario footprints presented here can be considered an approximate upper limit for what background system change can accomplish. Our analysis reveals that widespread technological change can reduce the average household carbon footprint across most countries by 2050, with substantial reductions projected to take place in the EU. Technological improvements can neutralize emissions associated with increasing consumption but do not offer enough mitigation potential to limit overall emissions to 1.5°C-compatible levels. As further emissions intensity reduction would be aggressively ambitious aside from some additional circularity and electrification efforts, a robust mitigation pathway for 1.5°C will require demand-side mitigation contributions nearing the upper limit estimated by the IPCC. Addressing consumption changes due to economic growth while simultaneously harnessing the decarbonization and development benefits of economic productivity will be critical to meeting emissions targets. The urgency of reducing emissions in line with a 1.5°C target is especially important for the EU, as any overshoots due to continued high levels of consumption will further exacerbate historical emissions inequality.

By calculating the emissions overshoots that would ensue without lifestyle change for multiple countries and regions, we demonstrate that non-technological mitigation is a critical component of 1.5°C mitigation pathways. Scenario modeling results from IAMs can obscure the contribution of demand-side mitigation, but the magnitude of necessary change indicated in this scenario suggests that lifestyle contributions might be better emphasized. We thus demonstrate how MRIO-based scenarios can complement traditional IAM scenarios for assessing climate change mitigation efforts, especially when substantially different background conditions could influence emissions embodied in household consumption. Future analysis can build on scenarios like the one presented here to understand how technological and structural changes over time impact the magnitude of reduction potentials from household lifestyle changes. A scenario that allows for an analysis of the most effective technological and lifestyle changes in a particular country or year can lead to more robust emission mitigation pathways that include demand-side change.

CRediT authorship contribution statement

Stephanie Cap: Conceptualization, Methodology, Formal analysis, Investigation, Software, Writing – original draft. **Arjan de Koning:** Conceptualization, Methodology, Software, Writing – review & editing. **Arnold Tukker:** Conceptualization, Writing – review & editing. **Laura Scherer:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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