

Carbon footprint reduction potential of consumption changes in five European countries in 2015, 2030, and 2050

Stephanie Cap^{a,*}, Sinja Li^{a,b}, Arjan de Koning^a, Antti Karjalainen^c, Michael Lettenmeier^{c,d}, Luca Coscieme^e, Arnold Tukker^{a,f}, Laura Scherer^a

^a Institute of Environmental Sciences (CML), Leiden University, Leiden, The Netherlands

^b Salacia Solutions Bv, Holbeinhuys 4th floor, Coolsingel 65, 3012 AC Rotterdam, The Netherlands

^c D-mat Ltd., Satusalepantie 5B, 00640 Helsinki, Finland

^d Department of Economics and Management, P.O. Box 66, University of Helsinki, 00014, Finland

^e Hot or Cool Institute, Berlin, Germany

^f Netherlands Organisation for Applied Scientific Research TNO, Den Haag, The Netherlands

ARTICLE INFO

Editor: Dr. Pan He

Keywords:

Climate change mitigation
Carbon footprint
Household consumption
Sustainable lifestyles
Behavior change
Environmentally extended input-output analysis

ABSTRACT

Limiting global warming to 1.5°C requires extensive socioeconomic and technological transformations. With approximately two-thirds of global greenhouse gas emissions linked to household consumption, reducing demand-side emissions through low-carbon lifestyle changes is critical. While major emissions hotspots and high-impact consumption changes are known, a cross-country prospective analysis of their emissions reduction potential has been missing. This study quantifies the avoided greenhouse gas emissions from 47 consumption changes across five diverse European countries. We assess how socioeconomic and technological changes influence emissions reduction potentials by comparing such potentials in a baseline year (2015) with those in 2030 and 2050 under a sustainable development scenario. Our findings highlight that the most effective mitigation options involve reducing conventional vehicle use, decarbonizing household heating, and shifting to predominantly plant-based diets. Though country-specific variation exists, we observed that the emissions reduction potentials of many consumption changes evolve proportionally to technological changes. Behaviors involving direct fossil fuel combustion, such as car travel or fossil-fueled heating, remain largely unabated by technological shifts without lifestyle change, thus increasing in relative mitigation potential. Changes relying on electricity substitution, such as switching to a heat pump, were most dependent on systemic decarbonization. These insights demonstrate which household-level actions consistently offer high emissions mitigation potential and which are more sensitive to broader system changes. Our results provide a clearer understanding of how individual climate change mitigation actions intersect with long-term industrial decarbonization strategies, supporting more targeted policymaking for demand-side climate change mitigation.

1. Introduction

Restricting global warming to a 1.5°C level is essential for maintaining a safe living space for humanity (Armstrong McKay et al., 2022; Ripple et al., 2024; Rogelj et al., 2018). The 2015 Paris Agreement aimed to limit global warming to well below 2°C, with efforts to stay within 1.5°C (UNFCCC, 2016). With limited time to reduce greenhouse gas (GHG) emissions and maintain the 1.5°C target (Lamboll et al., 2023; Riahi et al., 2022), mitigation efforts must be urgently accelerated across both industrial and household domains. Emissions mitigation pathways typically emphasize industrial technological development, neglecting

the possible contributions of lifestyle change (Creutzig et al., 2018). However, growing evidence indicates that industrial decarbonization alone will not suffice to limit global temperature increase to 1.5°C or 2°C without requiring carbon dioxide removal (Cap et al., 2024; de Koning et al., 2016; van Sluisveld et al., 2016; van Vuuren et al., 2018). As a result, more attention has recently been given to demand-side changes. In this paper, we understand demand-side or lifestyle changes as changes that reduce or shift consumption, or reduce the emissions intensity of consumption, e.g., through lower energy demand or waste, often leading to lower carbon footprints.

A robust evaluation of the carbon footprint reduction potential of

* Corresponding author.

E-mail address: s.cap@cml.leidenuniv.nl (S. Cap).

<https://doi.org/10.1016/j.spc.2025.08.018>

Received 11 November 2024; Received in revised form 15 August 2025; Accepted 23 August 2025

Available online 25 August 2025

2352-5509/© 2025 The Authors. Published by Elsevier Ltd on behalf of Institution of Chemical Engineers. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

lifestyle changes is essential for identifying the most effective options and integrating them into mitigation pathways. Yet, as interest in demand-side strategies has grown, it has become clear that quantitative data on the climate change mitigation potential of lifestyle changes remains limited, leaving policymakers and citizens with insufficient guidance for informed decision-making (Rogelj et al., 2018). This gap prompted an increase in research aimed at evaluating the effectiveness of various lifestyle changes in reducing emissions. Numerous studies employing life cycle assessment (LCA) and input–output analysis (IOA) methodologies emerged to quantify these impacts (Ivanova et al., 2020).

Because most 1.5°C-compatible scenarios require simultaneous supply- and demand-side transformations (Riahi et al., 2022; van Vuuren et al., 2018), the emissions reduction potentials of lifestyle changes are inevitably influenced by broader socioeconomic and technological developments. In the limited studies where lifestyle and technological change are explored together, such as dietary transitions (Bryngelsson et al., 2016) or electric vehicle adoption (Mendoza Beltran et al., 2020), the reduction potentials of lifestyle changes were found to be strongly influenced by technological assumptions beyond the scope of the lifestyle intervention. In recognition of the influence of industrial transformation on product or service system emissions, prospective LCA emerged to enable emissions assessment under varying technological scenarios. In advanced models, technological developments and efficiency gains are systematically applied to sectors based on scenarios from integrated assessment models (see Sacchi et al. (2022), for example). This approach enables specific lifestyle choices, such as driving an electric or conventional vehicle, to be evaluated not only under existing mainstream production systems but also in future contexts in which the changes are expected to be deployed at scale. However, product-LCA-based approaches are subject to truncation errors from system boundary choices, which may omit some upstream or downstream processes and associated emissions (Ward et al., 2018).

A similar integration of technological scenarios into assessments of lifestyle changes spanning the entire household consumption in a country has not been widely implemented, particularly within IOA frameworks. Prospective assessments of multiple lifestyle changes that account for adjusted emissions intensities from technological transformations remain limited. Prominent examples include a global-scale study (Girod et al., 2014), and regional assessments for the European Union (Costa et al., 2021), Sweden (Morfeldt et al., 2023), and Denmark (Bjørn et al., 2018). However, these analyses primarily evaluate combinations of lifestyle and technological changes needed to meet climate targets rather than examining how the mitigation potentials of lifestyle changes evolve over time. Consequently, a gap remains regarding prospective analyses that systematically explore how the emissions reduction potentials of multiple household lifestyle changes develop over time under different technological or socioeconomic scenarios. Addressing this gap is important for understanding the dynamic interaction between consumption changes and broader socioeconomic and technological transitions, ultimately informing more effective climate change mitigation strategies at national and regional scales.

Emissions should be reduced most rapidly within high-emissions countries to ensure a just climate transition (Chancel, 2022). The European Union (EU) has some of the most ambitious policies to address climate change in the world (Dupont et al., 2024), namely the net-zero emissions commitments by 2050 in the European Green Deal (European Commission, 2021), but also some of the most carbon-intensive lifestyles (Ivanova et al., 2016). This makes the EU a compelling case study for examining how the mitigation potentials of lifestyle changes evolve over time. Variations in income, infrastructure, economic structure, and urban form lead to substantial differences in carbon footprints both between and within European countries (Gill and Moeller, 2018; Hardadi et al., 2021; Ivanova et al., 2017; Ivanova and Wood, 2020; Jaccard et al., 2021; Ottelin et al., 2019). Thus, pathways to emissions reduction will necessarily vary both within and between EU countries.

To address the gap in understanding how the emissions reduction

potentials of lifestyle changes applied to all households in a country evolve under changing conditions, we assess various lifestyle changes in five EU countries in 2015, 2030, and 2050, accounting for technological and socioeconomic transformations aligned with a 1.5°C mitigation scenario. We aim to provide a clearer understanding of how individual climate change mitigation actions intersect with long-term industrial decarbonization strategies, supporting more targeted policymaking for demand-side climate change mitigation. While these scenario results apply to the EU region, the results can be relevant to similar high-income countries, and can also demonstrate a methodological contribution to be applied to other countries.

2. Literature review

Consumption-based emissions accounting, used to calculate carbon footprints, attributes supply chain emissions to final consumers based on the rationale that emissions are driven by consumption of goods and services (Tukker et al., 2020). Environmentally extended multiregional input-output (MRIO) analysis links the final consumption of goods and services to their associated life cycle environmental impacts. In these models, the global flows of goods and services are integrated with national environmental emissions accounts, enabling the attribution of local production impacts to global consumption patterns. Input-output analysis has been widely used to assess the carbon footprints or total embodied emissions of household consumption patterns (Hertwich and Peters, 2009; Ivanova et al., 2016; Jones and Kammen, 2011; Tukker et al., 2016) and any changes in emissions resulting from past changes to consumption patterns over time (Steen-Olsen et al., 2016; Wood et al., 2020).

Recently published research on the mitigation potential of household consumption changes has identified that, on average, the most effective strategies include reductions in individual motorized travel, air travel, the use of fossil-based energy in households, and the intake of animal-based products in diets (Ivanova et al., 2020; Koide et al., 2021b; Vita et al., 2019; Wynes and Nicholas, 2017; Wynes et al., 2018). This has led to an estimated reduction potential of 40–70% of total emissions from household lifestyle changes within domains such as mobility, housing, and nutrition (Creutzig et al., 2022), although this value may be lower for Europe when calculated with an IOA model (Moran et al., 2020).

MRIO models can represent adjustments to consumption, technology, and emissions intensity, which can be affected when households adopt a new consumption pattern (Wood et al., 2018). Carbon footprints calculated with MRIO models can be compared across products and regions, and with dynamic scenario models, these comparisons can also be made over time (Duchin et al., 2016). The input-output approach thus enables the calculation of global direct and indirect effects of changes to household consumption over time without truncation errors from setting system boundaries for a limited product-service system.

Although IOA-based studies of carbon footprints provide an internally consistent comparison of diverse lifestyle interventions and allow for scenario construction, prospective IOA remains limited to a few studies. These studies primarily focused on industrial technological change (Budzinski et al., 2023; Cap et al., 2024; de Koning et al., 2016; Duchin and Lange, 1994; Gibon et al., 2015; Wiebe et al., 2018; Wilting et al., 2008). To date, no prospective IOA studies have focused specifically on lifestyle changes and assessed a wide range of demand-side changes across multiple domains and countries. Given that lifestyle changes are likely to occur alongside broader decarbonization efforts, this gap in the literature is particularly noteworthy.

Beyond the missing prospective dimension in the climate change mitigation potential of lifestyle changes, other challenges remain in developing country-specific and individual-level recommendations for lifestyle transitions.

First, global or regional averages can obscure important variations between countries. Differences in socioeconomic or technological context make it difficult to generalize emissions reduction potentials

from one country to another, and divergent development trajectories can widen or narrow initial differences (Fricko et al., 2017; O'Neill et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017). While several country-level studies have examined national footprints and the mitigation potential of lifestyle changes (Carlsson Kanyama et al., 2021; Jones and Kammen, 2011; Koide et al., 2021a; Lekve Bjelle et al., 2018; Salo et al., 2021), comparative investigation across countries remains limited. Nonetheless, existing studies reveal some differences. For instance, housing changes were found to be relatively more important in Europe compared to the global average (Guan et al., 2025), and switching to renewable grid electricity was the most effective lifestyle change in Japan, compared to giving up a car in Finland (Koide et al., 2021b).

Second, emissions reduction potentials are rarely reported both as general population averages and values for only those individuals for whom a change is relevant. The former is useful for identifying high-impact interventions at scale, while the latter is better suited to guiding individual decision-making. Both are important data points for policymaking, as the impact of a lifestyle change can vary greatly based on expenditure patterns (Carlsson Kanyama et al., 2021; Guan et al., 2025), yet the highest-impact changes on average should be prioritized within national emissions mitigation strategies.

In sum, an assessment of population-level emissions reductions across countries in a current and future scenario across countries and over time is essential for developing a systematic approach to promoting widespread demand-side change, as required to meet the goals of the Paris Agreement.

3. Methods

3.1. Scoping countries and consumption change options

We selected Germany (DE), Spain (ES), Hungary (HU), Latvia (LV), and Sweden (SE) from the 27 European Union (EU27) countries based on differences in socioeconomic characteristics, consumption levels, and the energy mix (Figs. S1–S2). Income, household size, heating degree days, and electricity mix drive variation in household carbon footprints (Ivanova et al., 2017). Household final demand in EXIOBASE ranged from €4 998 (HU) to €19 630 (SE) per capita in 2015 basic prices (Fig. S2a), and average emissions intensities of final demand in Hungary and Latvia were double those of Sweden in 2015 (Fig. S2b). The countries capture geographic variation in heating demand, with heating degree-days in 2024 ranging from 4 798 in Sweden to 1 429 in Spain, while Germany and Hungary align closely with the EU average of 2 698, and Latvia falls between Sweden and the average (Eurostat, 2025). Household size ranged from 2 persons in Germany to 2.5 in Spain in 2015 (Eurostat, 2022b). Germany, Spain, and Latvia obtained most of their electricity from fossil-fuel sources in 2015, compared to a nearly completely renewable and nuclear mix in Sweden (Fig. 2c). Distance traveled by individualized motorized transportation also varied, with over 10 000 km per capita traveled on average per year in Sweden and Germany, and under 7 000 km per capita per year in Latvia, Hungary, and Spain (Fig. S2d). Diets varied the least across countries, with 5–6 kg of animal products purchased per person per week (Fig. S2e).

The consumption changes considered in this study originate from a literature review by Vadovics et al. (2024), which identified lifestyle change options across the domains of mobility, housing, nutrition, and leisure most relevant to the five countries studied. Both investment-focused (e.g., installing solar panels) and behavioral (e.g., adopting a plant-based diet) consumption changes were considered.

3.2. Modeling approach and data collection

Modeling household consumption changes in an MRIO model requires formulating a set of parameters that represent a simplified version of these changes within one or more of the four MRIO model components. The MRIO model components include direct intensity matrix of

emissions coefficients F , representing the GHG emissions per unit of industrial output; technical coefficients matrix A , representing the production recipe of industries per unit of output; vector of final demand of households y_{hh} , representing the total household consumption in a country; and vector of direct household emissions f_{yhh} , representing the emissions generated directly by households in a country (Miller and Blair, 2009).

The method of modeling lifestyle or consumption changes by modifying an MRIO model used here was first developed by Wood et al. (2018) and used to model lifestyle change by Vita et al. (2019) and Moran et al. (2020). The core of our approach consists of the same method of imposing changes on individual model components to create an adjusted MRIO model. Household lifestyle changes can be modeled by changing expenditure on product categories, such as in Wood et al. (2018) and Moran et al. (2020). Vita et al. (2019) expanded on the method of Wood et al. (2018) by calculating food and household energy layers to ensure equivalent service provision in some lifestyle changes. We similarly calculated our own food and household energy layers and extended this method to include household shelter and mobility service provision. For consumption change options involving a physical limit or modal shift, these layers were used to calculate the change factors to impose on the MRIO model components. An overview of our method is presented in Fig. 1.

For each consumption change in our dataset, we collected values from literature and public datasets to define the magnitude of each consumption or demand change for each of the MRIO model components in each country. Most data on passenger mobility were collected from various Eurostat databases (Eurostat, 2022a, 2022c, 2023c). Data for food supply and waste were taken from FAO (2023) and Gustafsson et al. (2013). Direct emissions and household energy use for various purposes were split for each country following household direct emissions data from OECD (2023), household energy balances from Eurostat (2023a), and detailed electricity use data from the Odyssee Database (Enerdata, 2023). From these data sources and those outlined in

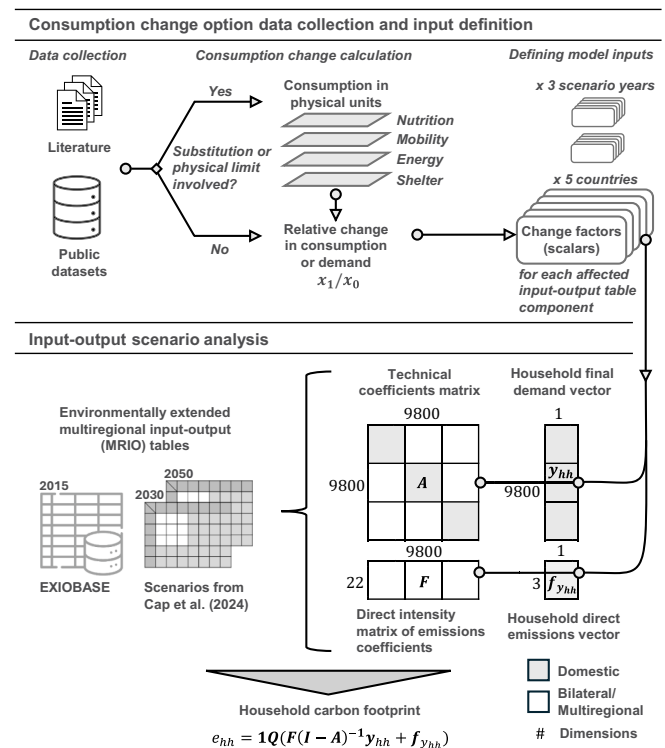


Fig. 1. Methodology for consumption change option data collection and parameterization for applying changes to the EXIOBASE and scenario input-output tables for years 2015, 2030, and 2050.

Supporting Information Sections 1–5, a set of change factors representing the change in demand or consumption from a lifestyle change was defined for each of the 200 product categories in y_{hh} , 22 emissions types in 200 product categories in F , 3 emissions types in $f_{y_{hh}}$, and the intermediate inputs of 200 product categories in A . A detailed explanation of the methodology for parameterizing each lifestyle option is presented in Supporting Information Sections 1–5. The change factors derived for each component of the 47 options in each country are available in Supplementary Data 1–4.

Changes to the final demand vector were the most common type of change resulting from our lifestyle changes. For example, *Switch to renewable electricity* involved eliminating household demand for fossil-based electricity and increasing demand for renewable electricity relative to the initial demand and amount of fossil-based electricity.

Most options involving household energy or mobility affected both household final demand and direct household emissions. For instance, replacing a conventional vehicle with public transportation involved a modal shift from conventional vehicle to public transportation, involving the same service provision measured in passenger-kilometers. Final demand for public transportation would increase relative to the starting distance traveled by public transportation and the new demand displaced from conventional vehicles, and direct emissions from households would be reduced by the share related to vehicle travel. Similarly, for replacing a gas boiler with a heat pump, household demand for fossil fuel heating products decreased and demand for electricity increased to maintain the same level of thermal comfort. Household direct emissions thus decreased by the proportion related to household space heating.

Shifts in household final demand were also reflected in the technical coefficient matrix for some consumption changes. In these cases, we assumed changes to household final demand would also involve a complete and immediate backwards cascade through the production system to fulfill altered consumer preferences. For instance, a shift to a vegan diet entailed a reduction of animal products and an isocaloric replacement with plant-based alternatives. Here, we also adjusted the technical coefficients for ‘Hotel and restaurant services’ to mirror the new diet, as animal food products were no longer an intermediate requirement for restaurant services.

In rare cases where consumer demand would theoretically shift the emissions of industries as a result of consumer preference, such as a shift to organic produce consumption, we modeled the change in the direct intensity matrix of emissions coefficients to represent these effects.

For each option, we modeled the upper limit of possible emissions reduction of each option, representing full uptake of the option across the entire relevant population in each country. Where the consumption change represented explicit partial completion or penetration, such as reducing space heating temperature by 2°C, moving 50% closer to work, or reducing floor space to 30 m² per capita, the change factors were scaled to reflect a fixed partial completion of this change based on the scaled value or the share of the population above or below the threshold each year (see Supplementary Data 5).

3.3. Calculating household carbon footprints with multiregional input-output analysis

Our model was developed using the EXIOBASE 3.8.2 MRIO model as a baseline for 2015 (Stadler et al., 2021; Stadler et al., 2018). EXIOBASE provides a resolution of 200 product categories, with comprehensive country-level resolution for the European Union, the focus for this analysis. Scenario models based on EXIOBASE developed in a previous study (Cap et al., 2024) were used for 2030 and 2050. These scenario models were developed from the Shared Socioeconomic Pathway 1 narrative of sustainable development compatible with a 1.5°C warming trajectory (SSP1-RCP1.9) (Riahi et al., 2017; Rogelj et al., 2018), but excluding explicit household change. These scenarios included a greater share of renewables in the electricity mix, industrial decarbonization

from electrification and emissions reduction technologies, an increase in gross domestic production from greater productivity and economic structure shifts, and changes to household consumption from increased income. Overall, these “background system” changes decreased the emissions intensities of nearly all production processes. More methodological details about this scenario construction are described in Cap et al. (2024).

Our analysis of carbon footprints included all major greenhouse gases (CO₂, CH₄, N₂O, SF₆, HFCs, and PFCs). IPCC AR6 global warming potentials with a 100-year time horizon (GWP100) were used to characterize the GHG emissions values to CO₂-equivalents (CO₂e) (IPCC, 2022).

The household carbon footprint can be calculated following the Leontief model for demand-driven consumption-based accounting (Leontief, 1970; Miller and Blair, 2009) (Eq. 1):

$$e_{hh} = 1Q(FLy_{hh} + f_{y_{hh}}) \quad (1)$$

Where e_{hh} is the sum of direct and indirect emissions attributed to household final consumption in a country; matrix of characterization factors Q is used to convert individual GHG emissions values to CO₂-equivalents; F is the direct intensity matrix of emissions coefficients; $L = (I - A)^{-1}$ is the Leontief inverse matrix or total requirements matrix per unit of final demand, with A as the technical coefficients matrix and I an identity matrix of the corresponding size; y_{hh} is a vector of final demand of households in a country; $f_{y_{hh}}$ is the vector of household direct emissions for a country; and 1 is an all-ones vector used for summation.

The emissions reduction potential of each consumption change Δe_{hh} was calculated as the difference between the household carbon footprint without interventions and the household carbon footprint with the intervention applied (Eq. 2):

$$\Delta e_{hh} = e_{hh} - e_{hh}' \quad (2)$$

The emissions reduction potential was normalized by the country population of the corresponding year n to arrive at a per-capita value (Eq. 3):

$$e_{pc} = \Delta e_{hh} n^{-1} \quad (3)$$

After calculating the emissions reduction potential relative to the baseline footprint, we used the thresholds established by Wynnes and Nicholas (2017) to classify the options into high-medium-low categories: 5% of average footprint reduction for high-impact, 1–5% for medium-impact, and less than 1% for low-impact.

3.4. Differentiating between average per-capita and subset-relevant impacts

We present our primary results as the reduction potential of the uptake of a consumption change at its theoretical maximum, distributed across the entire population. Many changes are relevant for most individuals. For instance, the EU average for vehicle stock is approximately one car for every two individuals (Eurostat, 2021a, 2021b), and only around 10% of Europeans avoid meat (Perez-Cueto et al., 2022). Others may only be relevant for a small subset of the population, such as those who own pets, drive SUVs, travel by airplane, or live in a building suitable for solar panels. However, where changes to housing can be expected to be distributed over all household members, this may not be the case for shared vehicles.

We also assessed the emissions reduction potential of consumption changes divided over only relevant individuals within the population for comparison with the average per-capita impacts. Assumptions for the percentage of the population eligible for certain changes are shared in Supplementary Data 7.

For selected options, we also present emissions intensities for relevant physical units to illustrate differences across countries and times, or the outsized contributions from high levels of consumption. While

monetary units in an IO model serve as proxies for physical quantities, converting these to physical units of service provision can provide a clearer interpretation of individual-level deviations in carbon footprints relative to national averages. We selected one lifestyle change per domain that had high or medium impact across all countries and was also theoretically linearly scalable. We also included *Avoid Flying* due to the association with emissions and wealth inequality (Ivanova and Wood, 2020).

3.5. Estimating financial effects from consumption changes

Shifts in lifestyle patterns can lead to changes in household

expenditure, influenced by both altered consumption habits and potential price changes. We estimated price changes based on 2015 EXIOBASE, calculating price changes as a percentage of the basic price in a category (e.g., ‘Motor vehicles’; see Supplementary Data 6). We also estimated the change in total household final demand from consumption changes in addition to specific price changes for product categories.

We present estimates for changes in household expenditure but do not calculate rebound effects. Extensive research exists on the varying potential rebound effects associated with the adoption of low-carbon consumption changes (Richter et al., 2024), and single actions will rarely achieve 1.5°C-compatible emissions reductions. Instead, extensive mitigation will require multiple changes, with financial savings

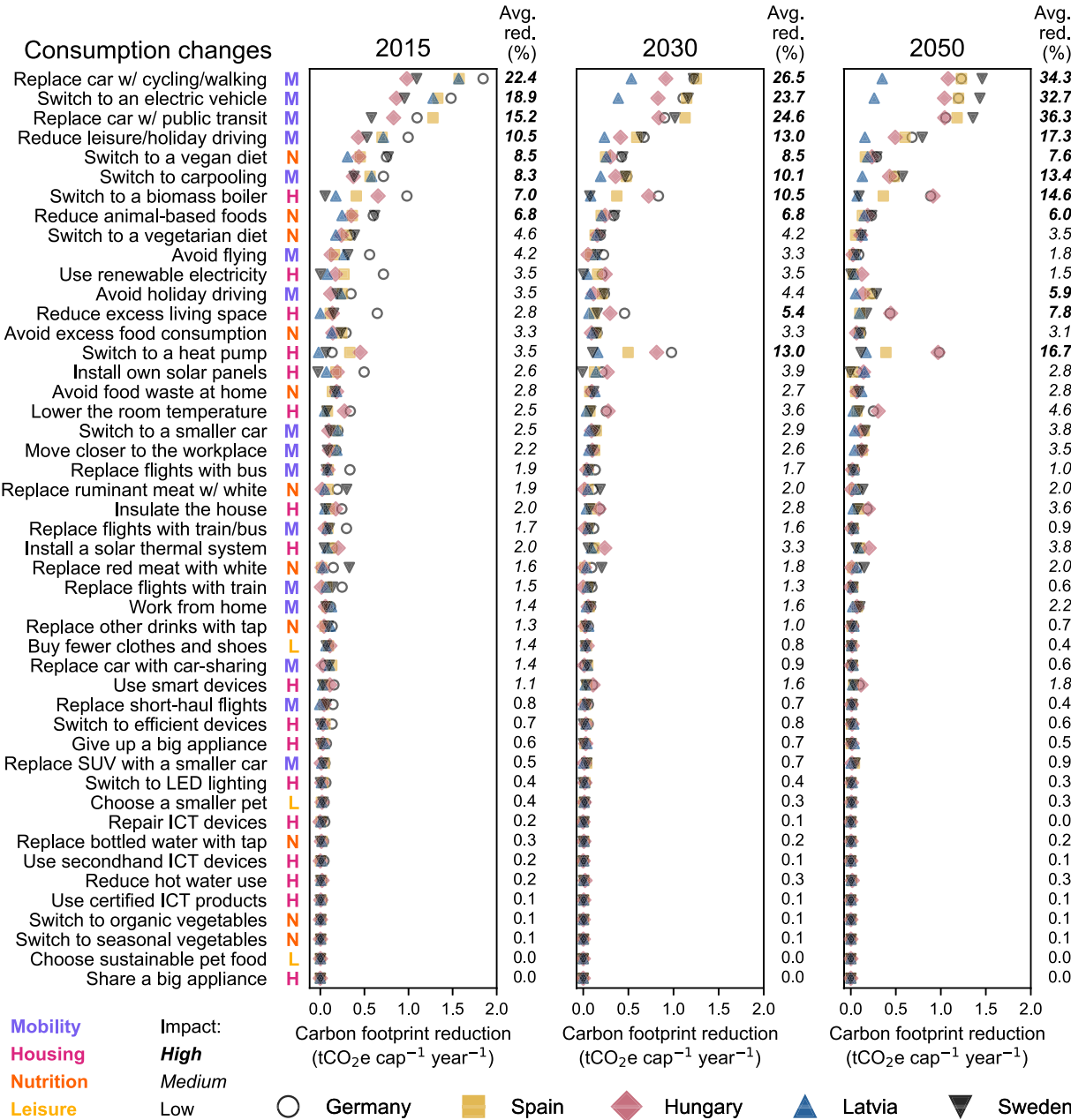


Fig. 2. Per-capita absolute carbon footprint reduction potential for 47 consumption change options in five EU countries in 2015, 2030, and 2050. The options are presented in descending order based on the average per-capita reduction potential for the five countries in 2015. Carbon footprint reduction potential is expressed as the reduction obtained without the consumption change in that year. Consumption changes are classified into domains of Housing (H), Mobility (M), Nutrition (N), and Leisure (L). Avg. red. (%) refers to the average relative carbon footprint reduction across the five countries. Bold and italic emphasis indicates high-impact options (>5%), italic emphasis indicates medium-impact options (1–5%), and regular text indicates low-impact options (<1%).

from some potentially funding others. By combining country- and year-specific emissions intensities with household expenditure changes, potential additional or avoided emissions can be estimated, though we avoid calculating precise rebound effects to prevent misrepresenting the impact of individual changes that are best considered as part of a broader lifestyle transformation.

4. Results

4.1. High-, medium- and low-impact consumption changes across countries and years

Across all five countries and scenario years, the majority of carbon footprint reduction potential is concentrated in a few high-impact options (Fig. 2). Nearly all these options fall within the mobility domain: *Replace car with cycling/walking* (1.0–1.4 tCO₂e 5-country average emissions mitigation potential over the three scenario years), *Switch to an electric vehicle* (0.9–1.2 tCO₂e), and reducing driving distance through *Reduce leisure/holiday driving* (0.5–0.7 tCO₂e) or individual driving distance with *Switch to carpooling* (0.4–0.5 tCO₂e). *Replace car with public transit* (0.9–1.2 tCO₂e) also offered substantial emissions reduction potential for four countries, although this option is not reported for Latvia due to issues reconciling the physical public transportation data and EXIOBASE. *Switch to a vegan diet* (0.2–0.5 tCO₂e) also maintained high emissions reduction potential over all countries and years studied. *Reduce animal-based foods* (0.2–0.4 tCO₂e), equivalent to eating a majority (80%) vegan diet, was high-impact in all countries and years aside from Latvia in 2015 (0.2 tCO₂e, 4% of footprint).

The prevalence of mobility changes in the highest impact categories can be attributed to both the substantial contribution of transportation to household footprints in the countries studied (an average of 31% in 2015, increasing to 39% in 2050, see Fig. S1), and the large share of personal vehicle emissions within transportation emissions. The share of emissions related to personal vehicle mobility within total household transportation emissions ranged from 63% (Sweden) to 79% (Spain, Hungary) in 2015, which increased to between 70% (Latvia) to 95% (Hungary) of emissions in 2050 under our scenario assumptions (Fig. S1). The share of food in the total household footprint ranged from 14% in Germany to 25% in Sweden in 2015, with the share remaining similar in all countries over time aside from Latvia (from 21% to 39%) (Fig. S1).

Consumption changes involving holiday travel patterns, such as *Avoid flying*, *Avoid holiday driving*, and the various options involving a modal shift from airplanes to ground transportation, were associated with medium-level impact for most countries and years at the general per-capita level (Fig. S3). Other medium-impact options related to mobility include reducing commuting travel by working from home, moving closer to work, or downsizing to a smaller vehicle. The nutritional changes *Switch to a vegetarian diet*, *Avoid excess food consumption*, and *Avoid food waste at home* also offered medium levels of emissions reduction over all countries and years.

Eleven of the options would each reduce emissions on a per-capita level by less than 1% in each of the selected countries and years, indicating that these options individually have a small emissions mitigation potential for the EU. These options, starting with *Choose a smaller pet*, are presented in descending order in Fig. S3.

4.2. Variation of consumption change impacts across years

Changes to production systems caused the absolute emissions reduction potential for many consumption changes to decrease from their 2015 values in 2030 and 2050. The decarbonization of the electricity system through an increasing share of renewable sources and carbon capture and storage caused the changes related to electricity use to decrease. *Use renewable electricity* decreased from a maximum reduction potential of 0.7 tCO₂e in Germany in 2015 to below 0.05

tCO₂e in all countries in 2050, aside from Hungary (0.1 tCO₂e in 2050). In 2030, the transitioning grid still allowed for this change to have at least a 4% carbon footprint reduction in Germany, Spain, and Hungary (Fig. S3). *Install solar panels* decreased in impact by an average of 70% in all countries aside from Latvia, where the reduction potential doubled from 0.1 tCO₂e to 0.2 tCO₂e (corresponding to a 1% to 7% potential decrease in average carbon footprint). In Latvia, the increased emissions mitigation potential for this change was driven by reduced demand for distribution and trade services for grid electricity proportional to self-production. Despite an emissions intensity reduction of more than 80% for this sector in all five countries in the background scenario, Latvia's remained at least twice as high as the other four.

Changes involving a modal shift from air to ground transportation also decreased in absolute reduction potential over each country and year. In the countries with the highest level of flight distance traveled (Germany and Sweden), flight travel made up an average of 19% of the household mobility footprint in 2015, which decreased to 5% in 2050 due to the emissions intensity reduction for air travel in the scenario model (Fig. S2d). This was due to the ambitious aviation decarbonization pathways outpacing the general decarbonization from greater productivity and industrial decarbonization for bus and rail outlined in the SSP1-RCP1.9 scenario in 2030 and 2050 (Cap et al., 2024).

The emissions mitigation potential of several housing interventions increased over time, driven by evolving consumption patterns, structural changes to industries, or a combination of both. *Switch to a heat pump* was the consumption change most positively influenced by technological transformations. Although initially only a high-impact intervention in Spain and Hungary, its emissions reduction potential increased in all countries on both an absolute and relative level. The most pronounced change on an absolute level was for Germany, where the reduction potential rose from 0.1 tCO₂e in 2015 to 1.0 tCO₂e in both 2030 and 2050, although the doubling of reduction potential from 0.5 to 1.0 tCO₂e resulted in a slightly larger relative footprint reduction in Hungary. The absolute emissions reduction for *Switch to a biomass boiler* decreased by 0.1 tCO₂e in Germany and Latvia, remained constant in Sweden and Spain, and increased by 0.2 tCO₂e in Hungary. The biomass production industry remained relatively unchanged compared to the evolving electricity mix in each country, resulting in a more stable reduction potential over time, but making biomass boilers less effective for emissions mitigation than heat pumps in the long term. Changes related to reducing fossil fuel use for space heating, such as *Lower the room temperature*, *Install a solar thermal system*, and *Insulate the house*, had a similar absolute reduction potential in each country over time, translating to an increased relative mitigation potential as footprints decreased over time. Other options targeting electricity-saving measures, like using smart devices or more efficient appliances, averaged lower absolute and relative emissions reduction potentials.

The emissions reduction potentials of the three options involving the elimination of conventional vehicles generally converged to similar values within a country by 2050, as the decarbonization of public transportation and electricity systems increased the relative effectiveness of this option. This was not the case for Latvia, where reductions in household direct emissions in the 2030 and 2050 scenarios (Fig. S1) led to a comparatively lower mitigation potential for these options relative to other countries. However, the emissions reductions from changes to mobility relative to other measures, such as reducing fossil fuel use for household heating, were influenced by the contribution of mobility to each country's carbon footprint and the share of mobility-related direct emissions in household footprints.

Diets were more similar across countries than mobility patterns, so the reduction potentials for dietary changes across countries converged over time. The emissions intensities of animal products decreased over time due to technological changes implied in SSP1-RCP1.9, such as overall efficiency improvements and targeted technical and structural changes to reduce non-CO₂ emissions (Frank et al., 2019), causing the dietary changes to mitigate relatively fewer emissions in future years

than the baseline year. This led to the options involving a reduction in meat and/or other animal products decreasing in absolute terms in all countries. Switching to a vegan or majority plant-based diet remained high-impact options over time as total carbon footprints decreased at a similar rate.

Some consumption changes with relatively small emissions reduction potentials maintained a consistent relative contribution across countries over time, while others declined both in absolute terms and as a share of the overall household carbon footprint. Interventions that primarily reduced electricity use through technological improvements, such as *Switch to LED lighting* or *Switch to efficient devices*, declined in both absolute and relative impact, reflecting the reduced marginal benefit of these changes under a decarbonized background system. Changes that reduced direct fossil fuel combustion by households, such as *Work from home* or *Use smart devices*, or those that lowered upstream agriculture emissions, such as *Switch to organic vegetables*, also had a small impact, but kept a constant or increasing relative contribution to overall household carbon footprint reduction across scenario years. Sufficiency-oriented options such as *Buy fewer clothes and shoes* decreased on an absolute level due to background system decarbonization, but also on a relative level due to these product categories decarbonizing faster than unmitigated household fossil fuel combustion.

4.3. Variation of consumption change impacts across countries

Due to the differences in baseline living space and household energy use for heating and electricity, the emissions reduction potential of *Reduce excess living space* varied by country. It remained a high-impact option in Germany in all years, even as absolute emissions reduction decreased from 0.6 tCO₂e in 2015 to 0.4 tCO₂e in 2050. In contrast, its impact increased in Hungary (from 0.1 tCO₂e to 0.4 tCO₂e) and in Latvia (0.0 tCO₂e to 0.1 tCO₂e) as average living area per capita increased beyond 30 m². In Spain and Sweden, the mitigation potential remained stable at medium-impact levels. *Lower the room temperature* increased to a high-impact option for Germany and Hungary driven by a high initial reliance on fossil fuels for space heating, which remained largely unmitigated in the background scenario. In Sweden, where emissions from household space heating were initially relatively low, reducing room temperature was nearly as effective in mitigating emissions as the installation of a heat pump. *Use renewable electricity* and *Install solar panels* offered effectively no mitigation potential for Sweden in any year.

Reducing household use of heating and mobility fuels (such as *Switch to public transport* or *Switch to a heat pump*) had nearly equivalent mitigation potentials in both Hungary and Germany in 2050. This contrasts with the case in Sweden or Spain, where mobility-related changes could mitigate at least 40% of household emissions options in 2050, while changes related to heating and living space could contribute a maximum of 15% (Spain) and 3% (Sweden) to total footprint reduction.

4.4. Variation of reduction potential between per-capita and individualized footprints

The emissions reduction potential for the average affected individual can be much higher than the average per capita for selected consumption changes (Fig. 3). Some emissions-intensive behaviors are practiced by a smaller subset of the population, so the greater reduction potential from ceasing these practices is derived from the larger associated starting footprint. *Replace SUV with a smaller car* had a low overall impact at a country level due to the small overall share of SUVs in vehicle fleets but increased by the largest factor on average across all options (from 15 in Germany to 40 in Latvia). Only a fraction of the population commutes with a motor vehicle, so attributing the savings to commuters for *Work from home* increased the impact by a factor 3.4 to 5.8. Scaling total emissions reduction of *Avoid flying* by only those who fly resulted in a mitigation potential 2.5–4.4 times greater than on a per-capita level. When considered per pet, the emissions savings from

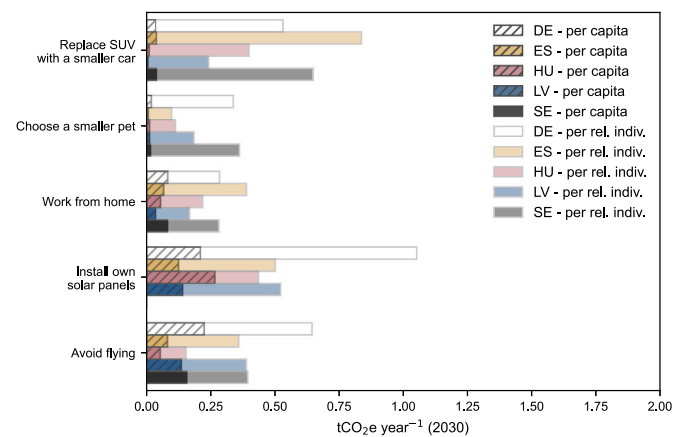


Fig. 3. Emissions reduction potential for selected consumption changes in 2030, divided by the total population (per capita) or the total relevant share of the population (per rel. indiv.). Countries are indicated by the ISO2 code: DE: Germany, ES: Spain, HU: Hungary, LV: Latvia, SE: Sweden.

reduced demand for pet food for *Choose a smaller pet* would be similar to an average individual undertaking a dietary change, such as *Reduce animal-based foods* in Germany, Latvia, and Sweden, and *Switch to a vegetarian diet* in Spain and Hungary. Although the impact of pet diets is comparable to that of humans, full adoption of this consumption change would still only reduce the total footprint by less than 1% in each country (Fig. 2). In contrast, *Install own solar panels* increased its emissions reduction potential by 1.6 (Hungary) to 5 (Germany) times when calculated for only those individuals living in a building suitable for solar panel installation. For this option, the increased reduction potential is not linked to a higher starting carbon footprint from above-average participation in emission-intensive practices.

The emissions intensities of the physical service provision of each consumption change decreased over time for all practices and countries (Fig. 4). However, the changes associated with direct household emissions, such as *Reduce excess living space* and *Replace car w/ cycling/walking* shown in Fig. 3 decreased less than those with only indirect emissions. While aviation emissions decrease in later scenario years, individuals with above-average flight activity may continue to have disproportionately high footprints – potentially exceeding the 1.5°C target with flight emissions alone. Assuming per capita carbon footprint targets of 2.4 tCO₂e for 2030 and 0.6 tCO₂e for 2050 (Cap et al., 2024), an individual could exceed the 2030 target by a round-trip flight from Frankfurt to Sydney, and the 2050 target with a round-trip flight to Tokyo. Emissions associated with additional housing are less drastic, but an additional 30 m² per capita in Germany would constitute over one-fourth of the per-capita target in 2030, and nearly the entire target in 2050.

4.5. Financial effects of consumption changes

Nearly all changes affect total final demand expenditure (Fig. 5). The extent of financial impact varied widely – for 19 of the changes studied, total final demand expenditure did not increase or decrease by more than 1%. Due to the large contribution of mobility to emissions and total final demand, the changes with the largest potential emissions reduction also have the largest financial effect. *Replace car w/ cycling/walking* reduced final demand expenditure by an average of 7% across all years and countries studied. This varied across countries, ranging from an average of 14% reduction in Latvia to 3% reduction in Sweden. The three changes involving less meat consumption offered the most financial savings after giving up a car. *Switch to a heat pump* was associated with a final demand expenditure increase in 2015 for Germany, Hungary, and Latvia and negligible effects in Spain and Sweden, but

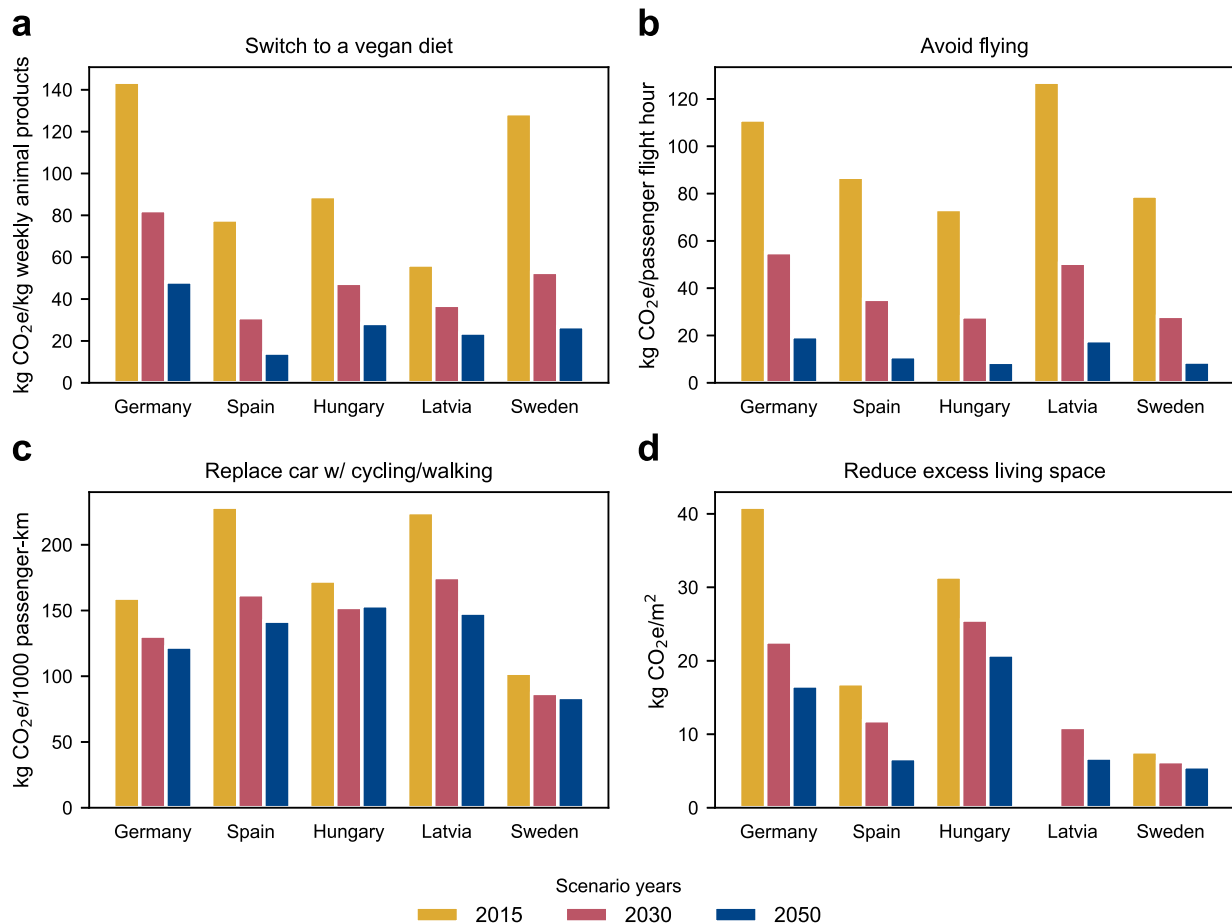


Fig. 4. Emissions intensities per corresponding physical unit for consumption changes in 2015, 2030, and 2050. a-d, Emissions intensities associated with (a) Switch to a vegan diet, (b) Avoid flying, (c) Replace car w/ cycling/walking and (d) Reduce excess living space. Corresponding physical units can be found in Fig. S2a for (a), Table S13 for (b), Fig. S2d for (c) and Fig. S2f for (d).

gradually evolved to small financial savings over time. Fewer options would increase financial expenditure than reduce it, with only six changes increasing average expenditure across years and countries by more than 1%. *Replace car w/ public transit* would increase final demand expenditure by an average of 8% across all countries and years, ranging from 1% in Spain and Hungary to 15% in Germany and 17% in Sweden, when accounting for vehicle, fuel, and maintenance-related expenses represented by household final demand. Assuming a moderately priced electric vehicle, *Switch to an electric vehicle* would also increase overall expenditure by 1–4%. All options involving a modal shift from flights to ground transportation were also associated with an increase in final demand.

5. Discussion

5.1. Comparison with literature

The consumption changes identified as high-impact over all countries and years in this study include several actions involving considerable changes to conventional vehicle mobility, including modal shifts and absolute reduction, and adoption of a vegan or plant-based diet. The high-impact options identified here were also noted as the most effective consumption-based emissions mitigation measures by [Ivanova et al. \(2020\)](#) in a systematic review. In many countries and years, reducing household demand for fossil fuels for space heating or overall demand for living space would offer medium to high levels of emissions reduction, confirming the amounts of emissions mitigation from sustainable shelter options in the EU ([Vita et al., 2019](#)). However, the overall

reduction potential depended on the initial use of fossil fuels for space heating and the electricity mix in each country. Compared to [Ivanova et al. \(2020\)](#) and [Vita et al. \(2019\)](#), we present lower estimates for emissions reduction from *Use renewable electricity* due to assumptions about the previous electricity mix. Although the household contribution to emissions reduction from this consumption change may decrease over time, this is not due to a decline in its absolute effectiveness, but rather because utility providers, rather than households, are implementing this change.

In contrast, *Switch to an electric vehicle* was less affected by changes in the background system than a heat pump. Driving an electric vehicle had fewer emissions than a conventional vehicle across all three scenario years. Previous research has also indicated that the GHG emissions during the use phase of electric vehicles are almost always lower than those from fuel combustion in conventional vehicles within the EU ([Faria et al., 2013](#); [Moro and Lonza, 2018](#)). However, our estimates do not include impacts from the alternative drivetrain and battery. Estimates of emissions embedded in battery manufacturing vary widely, but a lithium-ion battery produced in a baseline European context would add approximately 2 tCO₂e GHG emissions over the lifetime of the electric vehicle ([Kelly et al., 2020](#)). These emissions are expected to decrease in the 2030 and 2050 scenario years due to widespread industrial emissions reduction initiatives. Nevertheless, the overall emissions reduction potential of this consumption change would decrease with the inclusion of battery-related emissions, particularly when compared to switching to public or active transportation modes.

While the impact of changes to aviation was comparable to those in other studies on a distance ([Ivanova et al., 2020](#); [Ivanova et al., 2018](#))

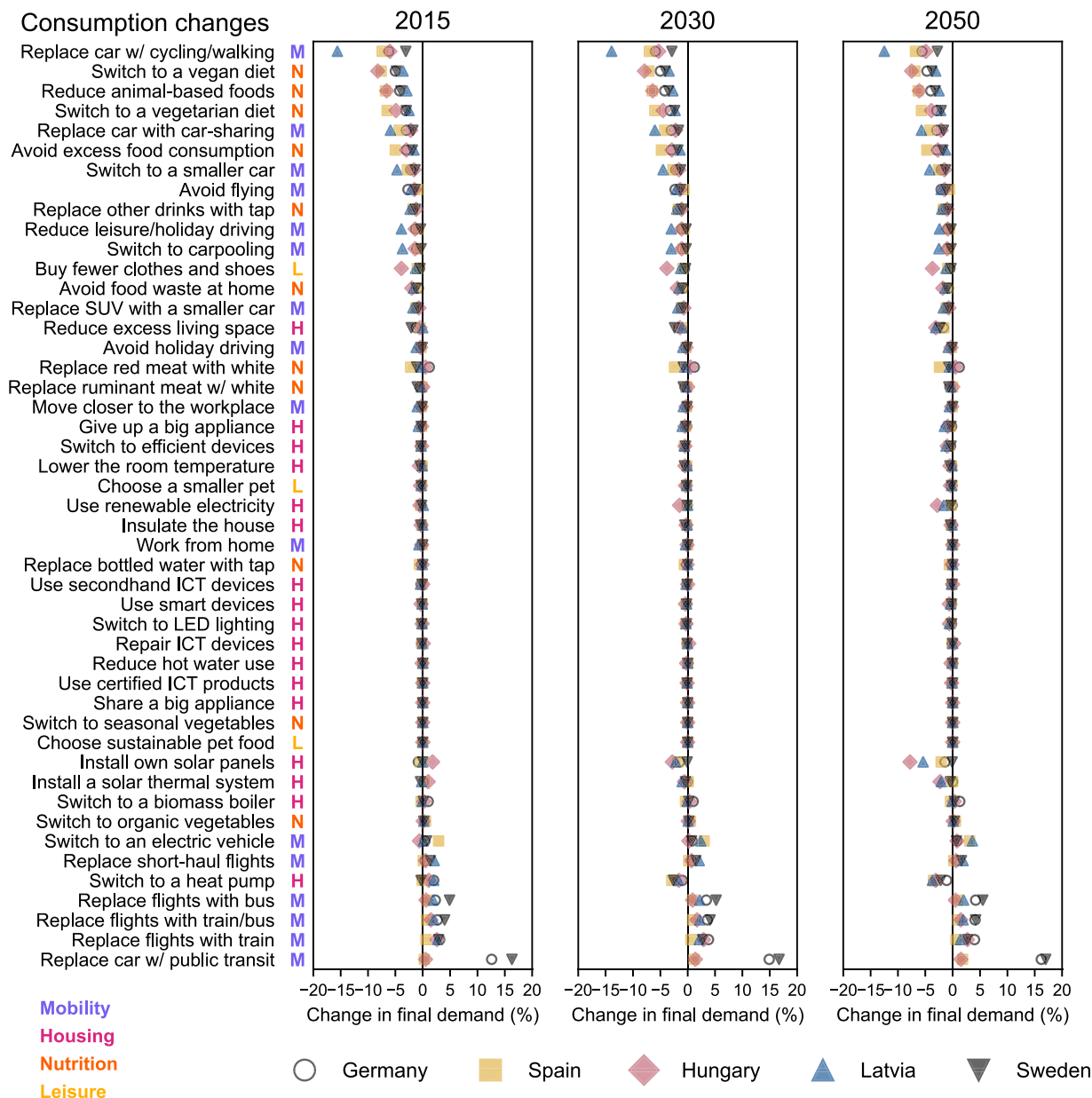


Fig. 5. Percent change in total per-capita household final demand expenditure after implementing a single consumption change for years 2015, 2030, and 2050. Consumption changes are classified into domains of Housing (H), Mobility (M), Nutrition (N), and Leisure (L).

and relative (Guan et al., 2025; Hu et al., 2019) basis, the overall contribution of reduced aviation to total carbon footprint reduction remains relatively small compared to vehicle mobility. Our analysis focused on the major greenhouse gases covered by the Kyoto Protocol, which excludes non-CO₂ effects from fuel combustion at high altitudes. These non-CO₂ effects could increase the global warming impacts of aviation emissions by 1.7–3 times (Lee et al., 2021; Lee et al., 2010). Additionally, our 2030 and 2050 scenarios also accounted for a 70% reduction in global aviation emissions between 2015 and 2050, as required for a 1.5°C pathway (Gidden et al., 2019). The shift to more sustainable fuels and the adoption of efficiency measures improved the relative positioning of aviation compared to other transportation modes, while public transportation systems decarbonized more slowly due to their already lower emissions baseline from electricity use in the reference year. Aviation emissions may also be marginally underestimated in some countries in EXIOBASE due to the attribution method for international bunker fuels (Rasul et al., 2024; Schulte et al., 2024; Stadler

et al., 2018). However, despite the EU’s aspirations to reach net-zero CO₂ emissions from aviation (van der Sman et al., 2021), these emissions are categorized as international bunker fuels and are therefore excluded from the emissions reduction measures under the Nationally Determined Contributions of the Paris Agreement. Even when considering the upper limits of climate impacts from non-CO₂ emissions, the potential reductions from eliminating aviation would be lower than those from phasing out internal combustion engine vehicles for personal travel. Thus, the overall potential for reducing aviation emissions seems less promising compared to domestic ground transportation, especially given that the latter is a larger source of emissions.

5.2. Limitations and future research needs

Despite the strengths of MRIO models, several challenges remain when modeling diverse lifestyle changes. To illustrate, modeling rooftop solar PV in an MRIO model highlights some limitations inherent to the

MRIO approach. The aggregated representation of product categories allows only rough estimates of the additional material burdens and financial investments. Hybrid IO-LCA models may be able to capture the effects of changing background systems with greater foreground system detail possible than in an MRIO model alone. MRIO models are not designed to model the self-production of electricity or the provision of electricity from one household to another. Additionally, the use of basic prices, as is common in MRIO modeling, can obscure important financial factors such as subsidies or price differences relative to the grid mix. Country-level estimates will be too broad to inform geographically targeted policy interventions, which would require solar irradiation or building stock estimates. In this case, subnational studies would be valuable for guiding localized policy design (Heinonen et al., 2020). While these limitations are particularly pronounced for rooftop solar PV modules, these limitations apply to most consumption changes modeled here to some degree.

Financial effects can influence the level of individual uptake of consumption changes, leading to an overall adoption rate lower than the theoretical potential. However, our approach calculated the change in final demand in basic prices while only considering limited price effects from consumption of a functionally different product, but not any other policies that may stimulate the uptake of low-carbon consumption changes through decreasing the household financial burden. Other MRIO-based studies accounted for feasible uptake rates for individual options (Moran et al., 2020; Vita et al., 2019). Consumption changes associated with more financial commitment may face barriers to uptake (Vadovics et al., 2024). However, it is also possible that options associated with financial savings could lead to re-spending, reducing the overall emissions mitigation potential. Financial savings do not necessarily indicate high potential uptake, as households can be slow to adopt energy-saving measures, even when these measures offer financial benefits over the lifetime of the product (Bertoldi, 2022). Constructing portfolios with different uptake rates of each consumption change and the effects of re-spending can explore the different levels of individual lifestyle change necessary to satisfy emissions reductions toward the 1.5°C target.

One of the drawbacks of modeling consumption changes at the maximum theoretical potential is that even if it is theoretically possible for a change to be made by most of a population, it may not be desirable for widespread adoption. For instance, European biomass resources are limited, and biomass boilers are associated with particulate matter emissions that are detrimental to human health (Las-Heras-Casas et al., 2018; Priedniece et al., 2022). In this case, a combination of different household heating technologies may offer heating emissions reduction with lower drawbacks (Palomba et al., 2020). Similar constraints and considerations may apply to several of the consumption changes examined in this study. Future research should explore the potential effects of implementing combinations of these practices across a population.

Our research focused on the effects of changing household consumption patterns, but excluded the emissions effects of final demand by governments, nonprofits serving households, and gross fixed capital formation. The carbon footprint of government expenditure in EXIO-BASE was estimated at 7% +/- 3% globally in 2007 (Ivanova et al., 2016), but public services can be as high as 19% in countries with a large welfare state (Ottelin et al., 2018). Accounting for capital goods used by industries leads to higher household carbon footprint estimates (Södersten et al., 2018). Accounting for the emissions from public infrastructure used by households, such as roads and buildings, as well as capital goods can provide better insight into the hidden emissions linked with household lifestyle change, and provide more accurate pathways to emissions reduction in line with the Paris Agreement target.

5.3. Policy implications

Because of the concentration of emissions reduction potential in

relatively few high-impact changes, the assumptions about household penetration are critical to assessing the likely rather than theoretical contribution of lifestyle changes to overall emissions mitigation. Our emissions reduction estimates for consumption changes assume full adoption of known technologies across the population, representing the maximum potential and serving as an upper limit for carbon footprint reduction. A carbon footprint reduction of at least 30% could be achieved in 2015 in the countries studied here by complete (100%) population uptake of a vegan diet, flight avoidance, and replacement of a conventional vehicle with an electric vehicle, public transport, or active transportation (Fig. S3). This reduction potential would increase in later scenario years. Supporting consumption changes with green public procurement initiatives that set higher emissions reduction standards than the market for dietary interventions (Smith et al., 2016), vehicle fleets and buildings (Lewis et al., 2023), can reduce carbon footprints of government services and contribute to making lifestyle changes more accessible for households.

The grid decarbonization modeled in 2030 and 2050 scenarios did not have the same effect on all technologies involving electrification. Of the options studied, *Switch to a heat pump* was the most sensitive to changes within the economy and industry. In this case, the heat pump efficiency along with the overall efficiency of the current heating system and electricity system determine the effectiveness of this intervention (Bayer et al., 2012; Kozarcin et al., 2020). Even in Germany, a country heavily reliant on fossil fuels for residential space heating, rapid installation of heat pumps and expansion of renewable energy can be one of the most effective approaches to reducing national fossil fuel use, without compromising the electrification of industrial processes and mobility (Altermatt et al., 2023). Switching from a natural gas boiler can also encourage a transition to electric cooking hobs, which may be particularly relevant in countries like Latvia and Hungary, where the quantities of fossil fuels used for cooking are comparable to those used for water heating (Eurostat, 2023b). In this way, we demonstrate the joint importance of structural improvements and individual consumption change in achieving large emissions reductions.

Our results for 2030 and 2050 reflect deep industrial decarbonization, but also rising incomes, which increase demand for mobility and thermal comfort. As a result, consumption changes targeting household fossil fuel combustion, particularly in mobility, contribute more to both absolute and relative carbon footprint reductions compared to the baseline year. Rising household incomes are likely to drive increases in vehicle ownership and travel distances in the EU (Ivanova and Wood, 2020; Lekve Bjelle et al., 2018; Steen-Olsen et al., 2016). Additionally, in many countries, increased income can lead to larger living spaces and higher household energy demand, which will constitute a substantial share of future carbon footprints if left unabated.

Our technological assumptions reflect the industrial transformations necessary to limit global temperature rise to 1.5°C, but current actions make a 2.7°C or 3°C scenario more likely (Climate Action Tracker, 2025; Hausfather and Peters, 2020). As our 2015 lifestyle change reduction potentials reflect a present-day system without additional decarbonization efforts, the results from this year can be interpreted as representative of a future in which current trends continue. Mobility-related lifestyle changes would remain among the most critical interventions even if progress on industrial decarbonization and renewable energy stalls. Addressing fossil fuel use for space heating and animal product consumption also remain high-impact actions on average, regardless of background system changes. EU consumption-based emissions have decreased by 19% between 2007 and 2016 (Wood et al., 2020). Based on our 2015 reduction potential results, our analysis indicates that a similar level of emissions reduction could be realized with a combination of the top three mobility interventions. Supporting a mobility transition, as outlined in the European Green Deal, is essential to preventing the unmitigated increase of mobility footprints beyond current levels.

Communicating households' role in climate change mitigation pathways will be essential for reaching the high levels of uptake

necessary for EU emissions reduction. All changes may be essential for certain households at different moments in a mitigation pathway. Emphasizing the joint responsibility of household change together with industrial decarbonization can reinforce how some changes, such as installing a heat pump, are most effective with joint household and industrial action. Changes involving technological substitution that replicate an industrial transition, such as switching to a renewable electricity contract, will need to be de-emphasized when industrial decarbonization materializes. While sufficiency-oriented changes may offer fewer marginal returns over time, these actions are still essential for reaching the drastic emissions reductions necessary for the Paris Agreement (Wiese et al., 2024), and should be communicated as important complements to high-impact changes.

6. Conclusions

Through a prospective MRIO analysis, this study provides new insights into mitigation potentials for consumption changes across multiple countries and years against a background of ambitious industrial decarbonization. By applying a consistent methodology to model lifestyle changes across diverse countries over time, we demonstrate that variations in mobility patterns, housing and heating systems, and overall industrial efficiency can influence the mitigation potential of similar interventions, even within the same region. We found that transitioning away from internal combustion engine vehicles, fossil fuels for home space heating, and animal products in diets offer the most potential for emissions reduction regardless of industrial decarbonization. Other changes, such as reducing demand for electricity use in the home through various efficiency measures, are also valuable, but their relative importance declines with a low-carbon electricity system. Comparing general per-capita effects with those individualized for a relevant share of the population also highlights that changes with high individual-level impact, such as reducing flying or installing solar PV panels, are important for individuals to pursue but may have a limited potential to reduce emissions on a national level. However, our findings also indicate that, even under assumptions of decarbonization within the aviation sector, long-haul flights can generate emissions that approach per-capita carbon footprint budgets compatible with a 1.5°C pathway.

Our work has several implications for demand-side climate change mitigation policy. First, direct household fuel use for transportation and space heating can be mitigated only to a limited extent through structural efficiency improvements that do not involve households, as indicated by their increasing share in carbon footprints over time. If these emission sources continue to rise with higher incomes, as historically observed, they will constitute the majority of a household carbon footprint in most EU countries. The mitigation potential of addressing these emissions sources increases most over time relative to any other source of household emissions. This finding underscores the urgency of EU policy initiatives aimed at achieving net-zero household heating and transportation by 2050.

Continued focus on each industry's 1.5°C-aligned mitigation pathway is crucial to achieving the emissions reduction potentials modeled in this study. In particular, we indicate the urgency of electricity mix decarbonization in maximizing the emissions mitigation potential from the introduction of heat pumps. While we do not observe that a more sustainable background system has a noticeable effect on the emissions reduction potential of switching to electric vehicles, our analysis was limited to the effects from use-phase emissions. When accounting for all upstream emissions including battery production, a shift to public transportation may offer a clearer pathway to individual emissions reduction from personal mobility.

In the future, the emissions mitigation potential of these consumption changes taken in parallel is an important line of research to better understand the relationship between the financial effects of consumption changes as well as any synergies from practices undertaken together. Furthermore, the potential uptake rates and optimal mix of

different practices in light of other tradeoffs need to be explored. The substantial emissions mitigation potential from demand-side changes, both now and in the future, reinforces the role these changes can play in contributing to climate change mitigation. However, the level of emissions mitigation realized depends on the interplay of consumer uptake, changes to emissions intensity via sustainable development of agriculture, industry, and service sectors, and any rebound effects from financial savings.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.spc.2025.08.018>.

CRedit authorship contribution statement

Stephanie Cap: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Sinja Li:** Writing – review & editing, Software, Investigation, Data curation. **Arjan de Koning:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Antti Karjalainen:** Writing – review & editing, Investigation, Data curation. **Michael Lettenmeier:** Writing – review & editing. **Luca Coscieme:** Writing – review & editing. **Arnold Tukker:** Writing – review & editing, Conceptualization. **Laura Scherer:** Writing – review & editing, Supervision, Software, Methodology, Investigation, Conceptualization.

Funding

The research presented here received funding from the European Union's H2020 Research and Innovation program under grant agreement no. 101003880. The sole responsibility for the content of this paper lies with the authors.

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.

Acknowledgements

We would like to thank the EU 1.5° Lifestyles Consortium for discussions related to this paper. We also thank Elli Latva-Hakuni, Eveliina Heikkala, Ursula Rinta-Jouppi, and Jari Kolehmainen for their support in collecting data.

References

- Altermatt, P.P., Clausen, J., Brendel, H., Breyer, C., Gerhards, C., Kemfert, C., Weber, U., Wright, M., 2023. Replacing gas boilers with heat pumps is the fastest way to cut German gas consumption. *Communications Earth & Environment* 4 (1), 56. <https://doi.org/10.1038/s43247-023-00715-7>.
- Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E., Rockström, J., Lenton, T.M., 2022. Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science* 377 (6611), eabn7950. <https://doi.org/10.1126/science.abn7950>.
- Bayer, P., Saner, D., Bolay, S., Rybach, L., Blum, P., 2012. Greenhouse gas emission savings of ground source heat pump systems in Europe: a review. *Renew. Sust. Energ. Rev.* 16 (2), 1256–1267. <https://doi.org/10.1016/j.rser.2011.09.027>.
- Bertoldi, P., 2022. Policies for energy conservation and sufficiency: review of existing policies and recommendations for new and effective policies in OECD countries. *Energy Buildings* 264, 112075. <https://doi.org/10.1016/j.enbuild.2022.112075>.
- Björn, A., Kalbar, P., Nygaard, S.E., Kabins, S., Jensen, C.L., Birkved, M., Schmidt, J., Hauschild, M.Z., 2018. Pursuing necessary reductions in embedded GHG emissions of developed nations: will efficiency improvements and changes in consumption get us there? *Glob. Environ. Chang.* 52, 314–324. <https://doi.org/10.1016/j.gloenvcha.2018.08.001>.
- Bryngelsson, D., Wirsén, S., Hedenus, F., Sonesson, U., 2016. How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture. *Food Policy* 59, 152–164. <https://doi.org/10.1016/j.foodpol.2015.12.012>.
- Budzinski, M., Wood, R., Zakeri, B., Krey, V., Strömman, A.H., 2023. Coupling energy system models with multi-regional input-output models based on the make and use

- framework – insights from MESSAGEix and EXIOBASE. *Econ. Syst. Res.* 1–19. <https://doi.org/10.1080/09535314.2022.2158065>.
- Cap, S., de Koning, A., Tukker, A., Scherer, L., 2024. (In)Sufficiency of industrial decarbonization to reduce household carbon footprints to 1.5°C-compatible levels. *Sustainable Production and Consumption* 45, 216–227. <https://doi.org/10.1016/j.spc.2023.12.031>.
- Carlsson Kanyama, A., Nässén, J., Benders, R., 2021. Shifting expenditure on food, holidays, and furnishings could lower greenhouse gas emissions by almost 40%. *J. Ind. Ecol.* 25, 1602–1616. <https://doi.org/10.1111/jiec.13176>.
- Chancel, L., 2022. Global carbon inequality over 1990–2019. *Nature Sustainability* 5 (11), 931–938. <https://doi.org/10.1038/s41893-022-00955-z>.
- Climate Action Tracker, 2025. The CAT thermometer. <https://climateactiontracker.org/global/cat-thermometer/>.
- Costa, L., Moreau, V., Thurm, B., Yu, W., Clora, F., Baudry, G., Warmuth, H., Hezel, B., Seydewitz, T., Ranković, A., Kelly, G., Kropp, J.P., 2021. The decarbonisation of Europe powered by lifestyle changes. *Environ. Res. Lett.* 16 (4), 044057. <https://doi.org/10.1088/1748-9326/abe890>.
- Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürges-Vorsatz, D., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. *Nat. Clim. Chang.* 8 (4), 260–263. <https://doi.org/10.1038/s41558-018-0121-1>.
- Creutzig, F., Roy, J., Devine-Wright, P., Díaz-José, J., Geels, F., Grubler, A., Maizi, N., Masane, E., Mulugetta, Y., Onyige, C., Perkins, P., Sanches-Pereira, A., Weber, E., 2022. Demand, services and social aspects of mitigation. In: *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Issue*. Cambridge University Press.
- de Koning, A., Huppes, G., Deetman, S., Tukker, A., 2016. Scenarios for a 2 °C world: a trade-linked input-output model with high sector detail. *Clim. Pol.* 16 (3), 301–317. <https://doi.org/10.1080/14693062.2014.999224>.
- Duchin, F., Lange, G.-M., 1994. *The Future of the Environment: Ecological Economics and Technological Change*. Oxford University Press.
- Duchin, F., Levine, S.H., Strömman, A.H., 2016. Combining multiregional input-output analysis with a world trade model for evaluating scenarios for sustainable use of global resources, part I: conceptual framework. *J. Ind. Ecol.* 20 (4), 775–782. <https://doi.org/10.1111/jiec.12303>.
- Dupont, C., Moore, B., Boasson, E.L., Gravey, V., Jordan, A., Kivimaa, P., Kulovesi, K., Kuzemko, C., Oberthür, S., Panchuk, D., Rosamond, J., Torney, D., Tosun, J., von Homeyer, I., 2024. Three decades of EU climate policy: racing toward climate neutrality? *WIREs Climate Change* 15 (1), e863. <https://doi.org/10.1002/wcc.863>.
- Enerdata, 2023. *Odyssey (Residential - Indicators)*. <https://www.indicators.odyssee-mur.e.u/energy-efficiency-database.html>.
- European Commission, 2021. European green deal – delivering on our targets. Publications Office of the European Union. <https://doi.org/10.2775/373022>.
- Eurostat, 2021a. Passenger mobility statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Passenger_mobility_statistics&table=0#Data.
- Eurostat, 2021b. Passenger road transport on national territory, by type of vehicles registered in the reporting country [road_pa_mov]. https://ec.europa.eu/eurostat/databrowser/view/road_pa_mov/default/table?lang=en.
- Eurostat, 2022a. Goods and passenger train traffic performance [rail_tf_trainmv]. https://doi.org/10.2908/RAIL_TF_TRAINMV.
- Eurostat, 2022b. Household characteristics by number of active persons [hbs_car_t312]. https://doi.org/10.2908/HBS_CAR_T312.
- Eurostat, 2022c. *Passenger cars, by type of motor energy and size of engine* European Commission. <http://data.europa.eu/88u/dataset/z8ftytrazfl4zvoljmcndg>.
- Eurostat, 2023a. Disaggregated final energy consumption in households - quantities [nrg_d_hhq]. https://ec.europa.eu/eurostat/databrowser/product/page/nrg_d_hhq.
- Eurostat, 2023b. Final energy consumption in households by type of fuel [nrg_bal_c]. <https://ec.europa.eu/eurostat/databrowser/view/ten00125/default/table?lang=en>.
- Eurostat, 2023c. Modal split of air, sea and inland passenger transport [tran_hv_ms_psmod]. https://ec.europa.eu/eurostat/databrowser/view/tran_hv_ms_psmod_cust_om_9207131/default/table?lang=en.
- Eurostat, 2025. Cooling and heating degree days by country - annual data [nrg_chdd_a]. https://doi.org/10.2908/NRG_CHDD_A.
- Faria, R., Marques, P., Moura, P., Freire, F., Delgado, J., de Almeida, A.T., 2013. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. *Renew. Sust. Energ. Rev.* 24, 271–287. <https://doi.org/10.1016/j.rser.2013.03.063>.
- Food and Agriculture Organization of the United Nations (FAO), 2023. *Food Balances / Food Balances (2010-)*. <https://www.fao.org/faostat/en/#data>.
- Frank, S., Havlík, P., Stehfest, E., van Meijl, H., Witzke, P., Pérez-Domínguez, I., van Dijk, M., Doelman, J.C., Fellmann, T., Koopman, J.F.L., Tabeau, A., Valin, H., 2019. Agricultural non-CO₂ emission reduction potential in the context of the 1.5 °C target. *Nat. Clim. Chang.* 9 (1), 66–72. <https://doi.org/10.1038/s41558-018-0358-8>.
- Fricko, O., Havlík, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolova, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D.L., Obersteiner, M., Pachauri, S., Rao, S., Schmid, E., Schoepp, W., Riahi, K., 2017. The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century. *Glob. Environ. Chang.* 42, 251–267. <https://doi.org/10.1016/j.gloenvcha.2016.06.004>.
- Gibon, T., Wood, R., Arvesen, A., Bergesen, J.D., Suh, S., Hertwich, E.G., 2015. A methodology for integrated, multiregional life cycle assessment scenarios under large-scale technological change. *Environ. Sci. Technol.* 49 (18), 11218–11226. <https://doi.org/10.1021/acs.est.5b01558>.
- Gidden, M.J., Riahi, K., Smith, S.J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D.P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J.C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlík, P., Hilaire, J., Hoelsy, R., Horing, J., Popp, A., Stehfest, E., Takahashi, K., 2019. Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. *Geosci. Model Dev.* 12 (4), 1443–1475. <https://doi.org/10.5194/gmd-12-1443-2019>.
- Gill, B., Moeller, S., 2018. GHG emissions and the rural-urban divide. A carbon footprint analysis based on the German official income and expenditure survey. *Ecol. Econ.* 145, 160–169. <https://doi.org/10.1016/j.ecolecon.2017.09.004>.
- Girod, B., van Vuuren, D.P., Hertwich, E.G., 2014. Climate policy through changing consumption choices: options and obstacles for reducing greenhouse gas emissions. *Glob. Environ. Chang.* 25, 5–15. <https://doi.org/10.1016/j.gloenvcha.2014.01.004>.
- Guan, Y., Shan, Y., Hang, Y., Nie, Q., Liu, Y., Hubacek, K., 2025. Unlocking global carbon reduction potential by embracing low-carbon lifestyles. *Nat. Commun.* 16 (1), 4599. <https://doi.org/10.1038/s41467-025-59269-1>.
- Gustafsson, J., Cederberg, C., Sonesson, U., Emanuelsson, A., 2013. *The Methodology of the FAO Study: "Global Food Losses and Food Waste-Extent, Causes and Prevention"*-FAO, 2011. SIK Institutet för livsmedel och bioteknik, In.
- Hardadi, G., Buchholz, A., Pauliuk, S., 2021. Implications of the distribution of German household environmental footprints across income groups for integrating environmental and social policy design. *J. Ind. Ecol.* 25 (1), 95–113. <https://doi.org/10.1111/jiec.13045>.
- Hausfather, Z., Peters, G., 2020. Emissions – the ‘business as usual’ story is misleading. *Nature* 577, 618–620. <https://doi.org/10.1038/d41586-020-00177-3>.
- Heinonen, J., Ottelien, J., Ala-Mantila, S., Wiedmann, T., Clarke, J., Junnila, S., 2020. Spatial consumption-based carbon footprint assessments - a review of recent developments in the field. *J. Clean. Prod.* 256, 120335. <https://doi.org/10.1016/j.jclepro.2020.120335>.
- Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: a global, trade-linked analysis. *Environ. Sci. Technol.* 43 (16), 6414–6420. <https://doi.org/10.1021/es803496a>.
- Hu, J., Wood, R., Tukker, A., Boonman, H., de Boer, B., 2019. Global transport emissions in the Swedish carbon footprint. *J. Clean. Prod.* 226, 210–220. <https://doi.org/10.1016/j.jclepro.2019.03.263>.
- IPCC, 2022. *Climate Change 2022: Mitigation of Climate Change. In: Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (P. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. Van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, & R. Fradera, Eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA. <https://doi.org/10.1017/9781009157926>.
- Ivanova, D., Wood, R., 2020. The unequal distribution of household carbon footprints in Europe and its link to sustainability. *Glob. Sustain.* 3 (e18), e18. <https://doi.org/10.1017/sus.2020.12>.
- Ivanova, D., Stadler, K., Steen-Olsen, K., Wood, R., Vita, G., Tukker, A., Hertwich, E.G., 2016. Environmental impact assessment of household consumption. *J. Ind. Ecol.* 20 (3), 526–536. <https://doi.org/10.1111/jiec.12371>.
- Ivanova, D., Vita, G., Steen-Olsen, K., Stadler, K., Melo, P.C., Wood, R., Hertwich, E.G., 2017. Mapping the carbon footprint of EU regions. *Environ. Res. Lett.* 12 (5), 054013. <https://doi.org/10.1088/1748-9326/aa6da9>.
- Ivanova, D., Vita, G., Wood, R., Lausset, C., Dumitru, A., Krause, K., Macsinga, I., Hertwich, E.G., 2018. Carbon mitigation in domains of high consumer lock-in. *Glob. Environ. Chang.* 52, 117–130. <https://doi.org/10.1016/j.gloenvcha.2018.06.006>.
- Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., Creutzig, F., 2020. Quantifying the potential for climate change mitigation of consumption options. *Environ. Res. Lett.* 15 (9), 093001. <https://doi.org/10.1088/1748-9326/ab8589>.
- Jaccard, I.S., Pichler, P.P., Tobben, J., Weisz, H., 2021. The energy and carbon inequality corridor for a 1.5 degrees C compatible and just Europe. *Environ. Res. Lett.* 16 (6), 064082. <https://doi.org/10.1088/1748-9326/abfb2f>.
- Jones, C.M., Kamm, D.M., 2011. Quantifying carbon footprint reduction opportunities for U.S. households and communities. *Environ. Sci. Technol.* 45 (9), 4088–4095. <https://doi.org/10.1021/es102221h>.
- Kelly, J.C., Dai, Q., Wang, M., 2020. Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. *Mitig. Adapt. Strateg. Glob. Chang.* 25 (3), 371–396. <https://doi.org/10.1007/s11027-019-09869-2>.
- Koide, R., Kojima, S., Nansai, K., Lettenmeier, M., Asakawa, K., Liu, C., Murakami, S., 2021a. Exploring carbon footprint reduction pathways through urban lifestyle changes: a practical approach applied to Japanese cities. *Environ. Res. Lett.* 16 (8), 084001. <https://doi.org/10.1088/1748-9326/ac0e64>.
- Koide, R., Lettenmeier, M., Akenji, L., Toivio, V., Amellina, A., Khodke, A., Watabe, A., Kojima, S., 2021b. Lifestyle carbon footprints and changes in lifestyles to limit global warming to 1.5 °C, and ways forward for related research. *Sustain. Sci.* <https://doi.org/10.1007/s11625-021-01018-6>.
- Kozarcianin, S., Hanna, R., Staffell, I., Gross, R., Andresen, G.B., 2020. Impact of climate change on the cost-optimal mix of decentralised heat pump and gas boiler technologies in Europe. *Energy Policy* 140, 111386. <https://doi.org/10.1016/j.enpol.2020.111386>.
- Lamboll, R.D., Nicholls, Z.R.J., Smith, C.J., Kikstra, J.S., Byers, E., Rogelj, J., 2023. Assessing the size and uncertainty of remaining carbon budgets. *Nat. Clim. Chang.* 13 (12), 1360–1367. <https://doi.org/10.1038/s41558-023-01848-5>.
- Las-Heras-Casas, J., López-Ochoa, L.M., Paredes-Sánchez, J.P., López-González, L.M., 2018. Implementation of biomass boilers for heating and domestic hot water in multi-family buildings in Spain: energy, environmental, and economic assessment. *J. Clean. Prod.* 176, 590–603. <https://doi.org/10.1016/j.jclepro.2017.12.061>.

- Lee, D.S., Pitari, G., Grewe, V., Gierens, K., Penner, J.E., Petzold, A., Prather, M.J., Schumann, U., Bais, A., Bernsten, T., Iachetti, D., Lim, L.L., Sausen, R., 2010. Transport impacts on atmosphere and climate: aviation. *Atmos. Environ.* 44 (37), 4678–4734. <https://doi.org/10.1016/j.atmosenv.2009.06.005>.
- Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestad, J., Gettelman, A., De León, R.R., Lim, L.L., Lund, M.T., Millar, R.J., Owen, B., Penner, J.E., Pitari, G., Prather, M.J., Sausen, R., Wilcox, L.J., 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.* 244, 117834. <https://doi.org/10.1016/j.atmosenv.2020.117834>.
- Lekve Bjelle, E., Steen-Olsen, K., Wood, R., 2018. Climate change mitigation potential of Norwegian households and the rebound effect. *J. Clean. Prod.* 172, 208–217. <https://doi.org/10.1016/j.jclepro.2017.10.089>.
- Leontief, W., 1970. Environmental repercussions and the economic structure: an input-output approach. *Rev. Econ. Stat.* 52 (3), 262–271. <https://doi.org/10.2307/1926294>.
- Lewis, A.N., Kaaret, K., Morales, E.T., Piirsalu, E., Axelsson, K., 2023. Green public procurement: a key to decarbonizing construction and road transport in the EU. Stockholm Environment Institute Stockholm. <https://doi.org/10.51414/sei2023.007>.
- Mendoza Beltran, A., Cox, B., Mutel, C., van Vuuren, D.P., Font Vivanco, D., Deetman, S., Edelenbosch, O.Y., Guinée, J., Tukker, A., 2020. When the background matters: using scenarios from integrated assessment models in prospective life cycle assessment. *J. Ind. Ecol.* 24 (1), 64–79. <https://doi.org/10.1111/jiec.12825>.
- Miller, R.E., Blair, P.D., 2009. *Input-Output Analysis: Foundations and Extensions*. Cambridge University Press.
- Moran, D., Wood, R., Hertwich, E., Mattson, K., Rodriguez, J.F.D., Schanes, K., Barrett, J., 2020. Quantifying the potential for consumer-oriented policy to reduce European and foreign carbon emissions. *Clim. Pol.* 20, S28–S38. <https://doi.org/10.1080/14693062.2018.1551186>.
- Morfeldt, J., Larsson, J., Andersson, D., Johansson, D.J.A., Rootzén, J., Hult, C., Karlsson, I., 2023. Emission pathways and mitigation options for achieving consumption-based climate targets in Sweden. *Commun. Earth Environ.* 4 (1), 342. <https://doi.org/10.1038/s43247-023-01012-z>.
- Moro, A., Lonza, L., 2018. Electricity carbon intensity in European member states: impacts on GHG emissions of electric vehicles. *Transp Res Part D: Transp Environ* 64, 5–14. <https://doi.org/10.1016/j.trd.2017.07.012>.
- OECD, 2023. *Air Emissions Accounts* OECD Environment Statistics (database). <http://data-explorer.oecd.org/>.
- O'Neill, B.C., Kriegl, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Chang.* 42, 169–180. <https://doi.org/10.1016/j.gloenvcha.2015.01.004>.
- Ottelin, J., Heinonen, J., Junnila, S., 2018. Carbon and material footprints of a welfare state: why and how governments should enhance green investments. *Environ. Sci. Pol.* 86, 1–10. <https://doi.org/10.1016/j.envsci.2018.04.011>.
- Ottelin, J., Heinonen, J., Nassen, J., Junnila, S., 2019. Household carbon footprint patterns by the degree of urbanisation in Europe. *Environ. Res. Lett.* 14 (11), 114016. <https://doi.org/10.1088/1748-9326/ab443d>.
- Palomba, V., Borri, E., Charalampidis, A., Frizzera, A., Cabeza, L.F., Karellas, S., 2020. Implementation of a solar-biomass system for multi-family houses: towards 100% renewable energy utilization. *Renew. Energy* 166, 190–209. <https://doi.org/10.1016/j.renene.2020.11.126>.
- Perez-Cueto, F.J.A., Rini, L., Faber, I., Rasmussen, M.A., Bechtold, K.-B., Schouteten, J.J., De Steur, H., 2022. How barriers towards plant-based food consumption differ according to dietary lifestyle: findings from a consumer survey in 10 EU countries. *International Journal of Gastronomy and Food Science* 29, 100587. <https://doi.org/10.1016/j.ijgfs.2022.100587>.
- Priedniece, V., Kirsanovs, V., Freimanis, R., Veidenbergs, I., Blumberga, D., 2022. Emissions and efficiency limits of small-scale biomass heating systems: regulations, standards, and ecolabels. *Environmental and Climate Technologies* 26 (1), 1032–1043. <https://doi.org/10.2478/rtuct-2022-0077>.
- Rasul, K., Schmidt, S., Hertwich, E.G., Wood, R., 2024. EXIOBASE energy accounts: improving precision in an open-sourced procedure applicable to any MRIO database. *J. Ind. Ecol.* 28 (6), 1771–1785. <https://doi.org/10.1111/jiec.13563>.
- Riahi, K., van Vuuren, D.P., Kriegl, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Streffer, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Chang.* 42, 153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>.
- Riahi, K., Schaeffer, R., Arango, J., Calvin, K., Guivarch, C., Hasegawa, T., Kjiang, K., Kriegl, E., Matthews, R., Peters, G., 2022. Chapter 3: Mitigation pathways compatible with long-term goals. In: Shukla, P.R., Skea, J., Slade, R., Al Khouridjaj, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R. (Eds.), *Contribution of working group III to the sixth assessment report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter03.pdf.
- Richter, J.L., Lehner, M., Elfström, A., Henman, J., Vadovics, E., Brizga, J., Plepys, A., Mont, O., 2024. 1.5° lifestyle changes: exploring consequences for individuals and households. *Sustainable Production and Consumption*. <https://doi.org/10.1016/j.spc.2024.07.018>.
- Ripple, W.J., Wolf, C., Gregg, J.W., Rockström, J., Mann, M.E., Oreskes, N., Lenton, T.M., Rahmstorf, S., Newsome, T.M., Xu, C., Svenning, J.-C., Pereira, C.C., Law, B.E., Crowther, T.W., 2024. The 2024 state of the climate report: perilous times on planet earth. *BioScience*. <https://doi.org/10.1093/biosci/biae087>.
- Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Khesghi, H., Kobayashi, S., Kriegl, E., Mundaca, L., Séférian, R., Vilarino, M.V., 2018. Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), *Special Report: 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*. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 93–174. <https://doi.org/10.1017/9781009157940.004>.
- Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., Luderer, G., 2022. PRospective EnvironMental impact asSEment (premise): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renew. Sust. Energ. Rev.* 160, 112311. <https://doi.org/10.1016/j.rser.2022.112311>.
- Salo, M., Savolainen, H., Karhinen, S., Nissinen, A., 2021. Drivers of household consumption expenditure and carbon footprints in Finland. *J. Clean. Prod.* 289, 125607. <https://doi.org/10.1016/j.jclepro.2020.125607>.
- Schulte, S., Jakobs, A., Pauliuk, S., 2024. Estimating the uncertainty of the greenhouse gas emission accounts in global multi-regional input-output analysis. *Earth Syst. Sci. Data* 16 (6), 2669–2700. <https://doi.org/10.5194/essd-16-2669-2024>.
- Smith, J., Andersson, G., Gourlay, R., Karner, S., Mikkelsen, B.E., Sonnino, R., Barling, D., 2016. Balancing competing policy demands: the case of sustainable public sector food procurement. *J. Clean. Prod.* 112, 249–256. <https://doi.org/10.1016/j.jclepro.2015.07.065>.
- Södersten, C.-J.H., Wood, R., Hertwich, E.G., 2018. Endogenizing capital in MRIO models: the implications for consumption-based accounting. *Environ. Sci. Technol.* 52 (22), 13250–13259. <https://doi.org/10.1021/acs.est.8b02791>.
- Stadler, K., Wood, R., Bulavskaya, T., Soedersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernandez, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., de Koning, A., Tukker, A., 2018. EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables. *J. Ind. Ecol.* 22 (3), 502–515. <https://doi.org/10.1111/jiec.12715>.
- Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., Koning, A., Tukker, A., 2021. EXIOBASE 3 (Version 3.8.2.). Zenodo. <https://doi.org/10.5281/zenodo.5589597>.
- Steen-Olsen, K., Wood, R., Hertwich, E.G., 2016. The carbon footprint of Norwegian household consumption 1999–2012. *J. Ind. Ecol.* 20 (3), 582–592. <https://doi.org/10.1111/jiec.12405>.
- Tukker, A., Bulavskaya, T., Giljum, S., de Koning, A., Lutter, S., Simas, M., Stadler, K., Wood, R., 2016. Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. *Glob. Environ. Chang.* 40, 171–181. <https://doi.org/10.1016/j.gloenvcha.2016.07.002>.
- Tukker, A., Pollitt, H., Henkemans, M., 2020. Consumption-based carbon accounting: sense and sensibility. *Clim. Pol.* 20 (sup1), S1–S13. <https://doi.org/10.1080/14693062.2020.1728208>.
- UNFCCC, 2016. Decision 1/CP.21: Adoption of the Paris Agreement. In: *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015. Addendum: Part two: Action taken by the Conference of the Parties at its twenty-first session. FCCC/CP/2015/10/Add.1. United Nations Framework Convention on Climate Change (UNFCCC)*, pp. 1–36.
- Vadovics, E., Richter, J.L., Tornow, M., Ozcelik, N., Coscieme, L., Lettenmeier, M., Csiki, E., Domröse, L., Cap, S., Puente, L.L., Belousa, I., Scherer, L., 2024. Preferences, enablers, and barriers for 1.5°C lifestyle options: findings from citizen thinking labs in five European Union countries. *Sustain Sci Pract Policy* 20 (1), 2375806. <https://doi.org/10.1080/15487733.2024.2375806>.
- van der Sman, E., Peerlings, B., Kos, J., Lieshout, R., Boonekamp, T., 2021. Destination 2050: a route to net zero European aviation. <https://www.seo.nl/en/publication/s/destination-2050-a-route-to-net-zero-european-aviation/>.
- van Sluisveld, M.A.E., Martínez, S.H., Daioglou, V., van Vuuren, D.P., 2016. Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. *Technol. Forecast. Soc. Chang.* 102, 309–319. <https://doi.org/10.1016/j.techfore.2015.08.013>.
- van Vuuren, D.P., Riahi, K., Calvin, K., Dellink, R., Emmerling, J., Fujimori, S., Kc, S., Kriegl, E., O'Neill, B., 2017. The shared socio-economic pathways: trajectories for human development and global environmental change. *Glob. Environ. Chang.* 42, 148–152. <https://doi.org/10.1016/j.gloenvcha.2016.10.009>.
- van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., van den Berg, M., Bijl, D.L., de Boer, H. S., Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., Hof, A.F., van Sluisveld, M.A.E., 2018. Alternative pathways to the 1.5°C target reduce the need for negative emission technologies. *Nat. Clim. Chang.* 8 (5), 391–397. <https://doi.org/10.1038/s41558-018-0119-8>.
- Vita, G., Lundström, J.R., Hertwich, E.G., Quist, J., Ivanova, D., Stadler, K., Wood, R., 2019. The environmental impact of green consumption and sufficiency lifestyles

- scenarios in Europe: connecting local sustainability visions to global consequences. *Ecol. Econ.* 164, 106322. <https://doi.org/10.1016/j.ecolecon.2019.05.002>.
- Ward, H., Wenz, L., Steckel, J.C., Minx, J.C., 2018. Truncation error estimates in process life cycle assessment using input-output analysis. *J. Ind. Ecol.* 22 (5), 1080–1091. <https://doi.org/10.1111/jiec.12655>.
- Wiebe, K.S., Bjelle, E.L., Többen, J., Wood, R., 2018. Implementing exogenous scenarios in a global MRIO model for the estimation of future environmental footprints. *J. Econ. Struct.* 7 (1), 20. <https://doi.org/10.1186/s40008-018-0118-y>.
- Wiese, F., Taillard, N., Balembois, E., Best, B., Bourgeois, S., Campos, J., Cordroch, L., Djelali, M., Gabert, A., Jacob, A., Johnson, E., Meyer, S., Munkácsy, B., Pagliano, L., Quoilain, S., Roscetti, A., Thema, J., Thiran, P., Toledano, A., Vogel, B., Zell-Ziegler, C., Marignac, Y., 2024. The key role of sufficiency for low demand-based carbon neutrality and energy security across Europe. *Nat. Commun.* 15 (1), 9043. <https://doi.org/10.1038/s41467-024-53393-0>.
- Wilting, H.C., Faber, A., Idenburg, A.M., 2008. Investigating new technologies in a scenario context: description and application of an input–output method. *J. Clean. Prod.* 16 (1, Supplement 1), S102–S112. <https://doi.org/10.1016/j.jclepro.2007.10.017>.
- Wood, R., Moran, D., Stadler, K., Ivanova, D., Steen-Olsen, K., Tisserant, A., Hertwich, E. G., 2018. Prioritizing consumption-based carbon policy based on the evaluation of mitigation potential using input-output methods. *J. Ind. Ecol.* 22 (3), 540–552. <https://doi.org/10.1111/jiec.12702>.
- Wood, R., Neuhoff, K., Moran, D., Simas, M., Grubb, M., Stadler, K., 2020. The structure, drivers and policy implications of the European carbon footprint. *Clim. Pol.* 20, S39–S57. <https://doi.org/10.1080/14693062.2019.1639489>.
- Wynes, S., Nicholas, K.A., 2017. The climate mitigation gap: education and government recommendations miss the most effective individual actions. *Environ. Res. Lett.* 12 (7), 074024. <https://doi.org/10.1088/1748-9326/aa7541>.
- Wynes, S., Nicholas, K.A., Zhao, J., Donner, S.D., 2018. Measuring what works: quantifying greenhouse gas emission reductions of behavioural interventions to reduce driving, meat consumption, and household energy use. *Environ. Res. Lett.* 13 (11), 113002. <https://doi.org/10.1088/1748-9326/aae5d7>.